IBA

TECHNICAL REVIEW

22

Light and Colour Principles

Blank pages in this document were not scanned so there may be occasional gaps in the page sequence.

IBA INDEPENDENT BROADCASTING AUTHORITY

IBA TECHNICAL REVIEW November 1984
ISSN 0308-423X

22 Light and Colour Principles

Contents

Technical Editor: Dr Henry Palmer, D.Sc., IBA Engineering Information Service

Additional Copies
Subject to availability, further copies of this *IBA Technical Review* may be obtained on application to Engineering Information Service, IBA Crawley Court, WINCHESTER, Hampshire, SO21 2QA.
No charge will be made for small quantities.

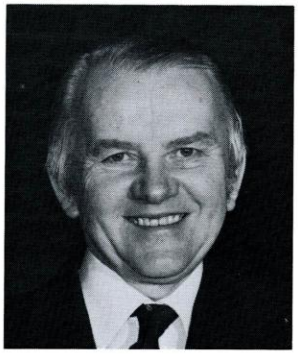
IBA INDEPENDENT BROADCASTING AUTHORITY

HEADQUARTERS: 70 Brompton Road, LONDON SW3 1EY. *Tel: 01-584 7011; Telex:* 24345
ENGINEERING DIVISION: Crawley Court, WINCHESTER, Hampshire, SO21 2QA. *Tel: 0962 823434; Telex: 477211*

Introduction

by J.B. Sewter

Assistant Director of Engineering (Network and Development)
Independent Broadcasting Authority



In Independent Broadcasting in the United Kingdom, the creative content of television programmes is the concern of individual programme companies but the IBA has overall responsibility for the maintenance of high technical standards. The quality of the picture at the programme source is of great importance because the transmission system, however good it may be, can never compensate fully for defects at the point of origin. It follows that IBA engineers are very much concerned with the technical performance of studio centres and the physical conditions necessary for high-quality colour reproduction.

Although the principal objective of a television system is the accurate reproduction of visual images, most engineers working in this field are obliged to concentrate on the electronic aspects. This is inevitable because the visual scene is converted to an electrical signal at a very early stage of the broadcasting chain, and reappears only at the extreme end of a complex signal path, on the receiver screen. Consequently, most effort is devoted to the processing, recording, distribution and transmission of electrical signals.

If the television broadcast engineer is to gain a thorough knowledge of his craft, his studies must include physical sciences other than electronics. Many excellent text books are available, dealing with such subjects as optics, photometry, colorimetry, etc., and this Technical Review is not intended to replace them. Its object is to provide a useful introduction to the aspects of photometry and colorimetry which are essential to the understanding of colour television, and to describe some practical developments which the IBA has carried out in this field.

Early chapters explain the fundamental concepts used in the quantitative measurement of light and colour. Definitions are given for the various units and the relationships between them, since this is an area where confusion can easily arise. The opportunity has been taken, in this volume, to incorporate the most recent modifications and standards adopted by the CIE (Commission Internationale de L'Eclairage). A brief historical outline of the CIE system of colour specification has been incorporated, but emphasis is given to derivation of the CIELUV 76 formulation, recommended for television applications. The evaluation of colour differences using a three-dimensional colour space as the basis for an objective system of measurement is discussed.

It is fortunate that the science of colorimetry was already well advanced when high quality colour television was first introduced. It provided a firm foundation for a signal processing system which gives excellent colour reproduction, together with the necessary attributes of compatibility and reverse compatibility. Much of this volume is concerned with the application of colorimetry in television broadcasting.

During the past few years, broadcasters have achieved a more widespread understanding of colorimetry and its importance in colour television. Thanks to the revolutionary advance of solid-state electronics, the necessary multiple measurements and complex calculations can now be handled with speed and accuracy by a versatile, low-cost, microcomputer. These developments, together with recent improvements in inexpensive optical equipment, enabled IBA engineers to construct a transportable test rig, capable of a wide range of colorimetric measurements. One chapter describes this computer-controlled spectrophotometric equipment, as used for the analysis and optimisation

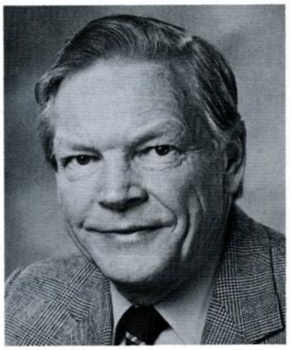
of the colorimetric performance of television cameras. Another describes a different application of the same equipment, to achieve similar analyses of display-tube phosphors and other luminous sources.

It is planned to give further consideration to colour in television in another *IBA Technical Review* to be published later. This second volume will contain an overall review of the subject, including the design of systems related to the psychophysics of the eye. It will also include contributions by specialists on viewing conditions for picture quality assessment, and on film and lighting for colour television.

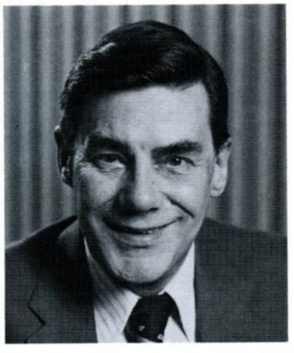
The Measurement of Light

by Prof. R.W.G. Hunt and P.J. Darby

ROBERT W.G. HUNT received a B.Sc. (Physics) from Imperial College London, and Ph.D. and D.Sc. from London University for work in colour vision and colour reproduction. He joined the Kodak Research Laboratories in 1946, working on materials for still and cine photography. He retired as Assistant Director of Research at Kodak in 1982. He is now Visiting Professor of Physiological Optics at the City University in London, and a colour Consultant in Science and Technology. His book on *The Reproduction of Colour* is now in its third edition. He is currently President of the International Colour Association (AIC). From 1975 to 1983 he was Chairman of the Colorimetry Committee of the International Commission on Illumination (CIE).



PHILIP DARBY, MBE, C.Eng., MIERE, began his broadcasting career at the BBC where he held several engineering posts. On joining the IBA in 1955 he immediately wrote himself into broadcasting history by completing the log as Senior Shift Engineer on duty at Croydon transmitting station on the first night of ITV. Subsequently he was at Emley Moor and Engineer-in-Charge of Dover transmitting station. He was Head of the IBA Quality Control Section from its formation in 1967 until 1981. He is now Senior Assistant to the Head of the IBA Engineering Information Service and also contributes to the work of the CCIR and CIE. He is married and lives in Hampshire.



Synopsis

Photometry uses the response of the human eye at different wavelengths of light to establish a system of photometric units directly related to the radiometric units used in Physics. On this basis, units are defined for the measurement of luminous flux, luminous intensity, illuminance, luminance, luminous efficiency, light exposure and optical density. While photometry is concerned with the total visual effect of the light, spectrophotometry takes account of the amount of light at each wavelength and provides methods of measurement appropriate to the study of colour phenomena. A procedure is described for measurement of the spectral power distribution of light sources and this is followed by a description of the standard CIE conditions for the measurement of spectral reflectance factor and spectral transmittance. The chapter concludes with a discussion on light sources, including Planck's law of radiation, the concept of colour temperature and definitions of the CIE standard illuminants.

INTRODUCTION

The fundamental input to any television system is radiant energy in the form of light. Photometry, the measurement of light, is therefore of great importance to television engineers.

The quantities normally encountered in broadcast engineering can be expressed in objective terms such as power, voltage etc., using units that are independent of the observer. The perception of light and colour by the eye are partially subjective phenomena, however, akin to the appreciation of music by the ear and brain. Television systems intended to produce particular perceived effects (faithfulness and realism) must be designed and tested in appropriate ways, taking into account these subjective aspects.

The human eye responds to a band of electromagnetic radiation centred on a frequency of approximately 540×10^{12}Hz, corresponding to a wavelength of 555nm.

In normal daylight the visible spectrum extends from about 380nm to about 780nm.* The corresponding frequency bandwidth of 4×10^{14}Hz is narrow compared with the known electromagnetic

* The response is narrower at very low light levels.

spectrum, which, in nature, extends from about 10Hz to 3×10^{24}Hz.

The relative response of the normal human eye to monochromatic light at the different spectral frequencies has been determined experimentally by the Commission Internationale de L'Eclairage (CIE). This is known as the photopic spectral luminous efficiency function and is illustrated in Fig. 1. The symbol for this function is $V(\lambda)$ and it is usually expressed as a function of the wavelength of light (in air).

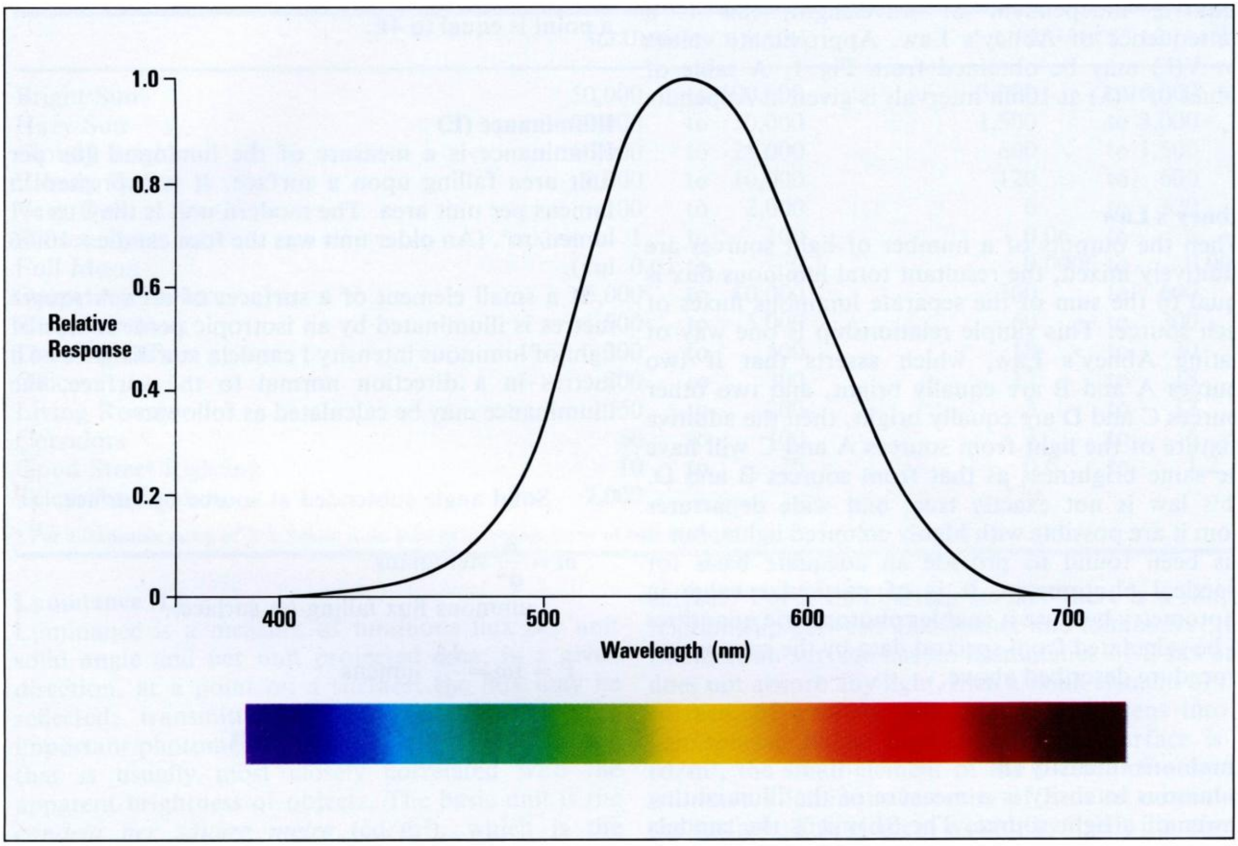


Fig. 1. The photopic luminous efficiency function $V(\lambda)$.

The photopic spectral luminous efficiency function serves as a link between the subjective response of the human eye and normal physical measurement techniques. It thus provides the basis for a group of photometric units which are directly related to the radiometric units used in physics.**

** In this Review all 'photometric' units are to be understood to refer to light as perceived by the CIE Standard Eye. All radiometric units are expressed in the normal SI (Systeme Internationale) physical quantities such as watts/m^2/MHz. The recommended practice is given in BS 4727.

PHOTOMETRIC MEASURES AND THEIR UNITS

Luminous Flux (F)

Luminous flux is a measure of the quantity of light emitted, transferred, or received, per second. The unit of luminous flux is the *lumen* (lm), which is defined as the luminous flux of a beam of monochromatic radiation whose radiant flux is 1/683 Watt and whose frequency is 540×10^{12}Hz (closely equivalent to a wavelength of 555 nm).

Calculating Photometric Quantities from Spectral Radiant Data

If the amount of radiant flux present at each wavelength of a radiation is known, it is possible to calculate the total luminous flux by weighting the amount of radiant flux at each wavelength in accordance with the photopic spectral luminous efficiency function, $V(\lambda)$, and summing all these weighted values throughout the spectrum. Thus, if the radiant fluxes in Watts at wavelengths 1,2,3, etc.,

are P_1, P_2, P_3, etc., and the values of $V(\lambda)$ at the same wavelengths are V_1, V_2, V_3, etc., then the luminous flux, F, in lumens, is given by:

$$F = 683\,(P_1V_1 + P_2V_2 + P_3V_3 + \ldots\ldots)\ \text{lumens}$$

The factor 683 is introduced because, at the wavelength of 555nm, the value of $V(\lambda)$ is unity. The summation is usually carried out over the wavelength range 380 to 780nm at 10nm intervals. This summation is a valid procedure because, to a sufficiently good approximation, luminous fluxes are additive, independent of wavelength; this is a consequence of Abney's Law. Approximate values for $V(\lambda)$ may be obtained from Fig. 1. A table of values of $V(\lambda)$ at 10nm intervals is given in Appendix A.

Abney's Law

When the outputs of a number of light sources are additively mixed, the resultant total luminous flux is equal to the sum of the separate luminous fluxes of each source. This simple relationship is one way of stating Abney's Law, which asserts that if two sources A and B are equally bright, and two other sources C and D are equally bright, then the additive mixture of the light from sources A and C will have the same brightness as that from sources B and D. This law is not exactly true, and wide departures from it are possible with highly coloured lights; but it has been found to provide an adequate basis for practical photometry. It is of particular value in photometry because it enables photometric quantities to be calculated from spectral data by the summation procedure described above.

Luminous Intensity (I)

Luminous intensity is a measure of the illuminating power of a light source. The SI unit is the candela which is the luminous intensity in a given direction of a source emitting a monochromatic radiation of frequency 540×10^{12}Hz, the radiant intensity of which in that direction is 1/683 Watt per steradian*. Hence the luminous intensity of a point source in a particular direction is equal to the luminous flux emitted per steradian in that direction. The general relationship for a point source is given by the equation:

$$I = \frac{F}{\omega}\ \text{candela (cd)}$$

where I = luminous intensity
F = luminous flux within solid angle considered
ω = solid angle

An Isotropic point source (that is, one that radiates equally in all directions) would emit a total luminous flux of $4\pi I$ lumens, since the total solid angle around a point is equal to 4π.

Illuminance (E)

Illuminance is a measure of the luminous flux per unit area falling upon a surface. It is expressed in lumens per unit area. The modern unit is the Lux = 1 lumen/m^2. (An older unit was the foot candle = 10.76 lux).

If a small element of a surface, of area A square metres is illuminated by an isotropic point source of light of luminous intensity I candela at a distance of d metres in a direction normal to the surface, the illuminance may be calculated as follows:-

Solid angle subtended at source by surface,

$$\omega = \frac{A}{d^2}\ \text{steradians}$$

Luminous flux falling on surface,

$$F = I\omega = \frac{IA}{d^2}\ \text{lumens}$$

$$\text{Illuminance, } E = \frac{F}{A} = \frac{I}{d^2}\ \text{lux}$$

This last relationship introduces the inverse-square law of illumination. This law is almost self-evident, since the luminous flux is constant for a given solid angle, and its amount per unit area must therefore vary inversely with the square of the distance from the source. Equally clear is the cosine law of illumination. If the light from a source is inclined to the normal to a surface by an angle θ, the flux falling on a given area will be reduced in proportion to the cosine of this angle. Thus the complete expression for surface illumination from a point source of light

* The steradian is the unit used for expressing solid angles—one steradian is the solid angle which, having its vertex in the centre of a sphere, cuts off an area of the surface of the sphere equal to the area of a square with sides of length equal to the radius of the sphere.

takes account of the distance, luminous intensity, and direction of the source:-

$$E = \frac{I \cos \theta}{d^2} \text{ lux}$$

Colour television requires studio illuminances in the region of 2000 lux. Levels of 100,000 lux can be experienced in sunlight. A list of typical illuminances is given in Table I.

reflecting (non-diffusing) surface or 'specular' reflector.

With another type of surface, the luminous flux emitted in a direction θ degrees to the normal is directly proportional to cos θ. In this case, the emitted luminous flux level and the area projected on a plane at right angles to the viewing direction both follow the same cosine law with the result that the surface appears to be of equal luminance from all directions. Such a surface is called a Lambertian surface. For a Lambertian surface there is a simple relationship between illuminance and luminance. If a Lambertian surface has an illuminance of E lux and does not absorb any light, then a small element of the surface, of area ds, will emit E.ds lumens into a hemisphere. If the luminance of the surface is L cd/m², the small element of the surface of area ds, will have a luminous intensity of L.ds cd normal to the surface. This element would, by itself, illuminate a hemisphere of radius r as shown in Fig. 2.

TABLE 1: TYPICAL LEVELS OF ILLUMINATION AND LUMINANCE

	ILLUMINANCE (LUX)	LUMINANCE* (CD/M²)
Bright Sun	50,000 to 100,000	3,000 to 6,000
Hazy Sun	25,000 to 50,000	1,500 to 3,000
Cloudy Bright	10,000 to 25,000	600 to 1,500
Cloudy Dull	2,000 to 10,000	120 to 600
Very Dull	100 to 2,000	6 to 120
Sunset	1 to 100	0.06 to 6
Full Moon	0.01 to 0.1	0.0006 to 0.006
Operating Theatre	5,000 to 10,000	300 to 600
Shop Windows	1,000 to 5,000	60 to 300
Drawing Offices	300 to 500	18 to 30
Offices	200 to 300	12 to 18
Living Room	50 to 200	3 to 12
Corridors	50 to 100	3 to 6
Good Street Lighting	10 to 20	0.6 to 1.2
Television Studios	2,000	120

* For a luminance factor of 20% (which is the average luminance factor of typical scenes).

Luminance (L)

Luminance is a measure of luminous flux per unit solid angle and per unit projected area, in a given direction, at a point on a surface; the flux may be reflected, transmitted, or emitted. It is a very important photometric measure because it is the one that is usually most closely correlated with the apparent brightness of objects. The basic unit is the *candela per square metre* (cd/m²), which is the luminance produced by a luminous intensity of 1 candela uniformly distributed over a surface of 1 square metre. For other luminous intensities, I, and other areas, A, the luminance is given by:

$$L = \frac{I}{A} \text{ cd/m}^2$$

Surfaces vary greatly in the way they reflect or radiate light. An ideal plain mirror is a perfectly

At a particular angle to the normal, θ, there is an elemental ring on the surface of this sphere which is subject to a luminous intensity of L.ds.cosθ cd.

The width of the ring is r.dθ and the circumference of the ring is 2πr.sinθ.

The solid angle subtended at the source by the elemental ring is, therefore:

$$\omega = \frac{\text{area}}{r^2} = \frac{2\pi r^2 \sin\theta d\theta}{r^2} = 2\pi \sin\theta d\theta$$

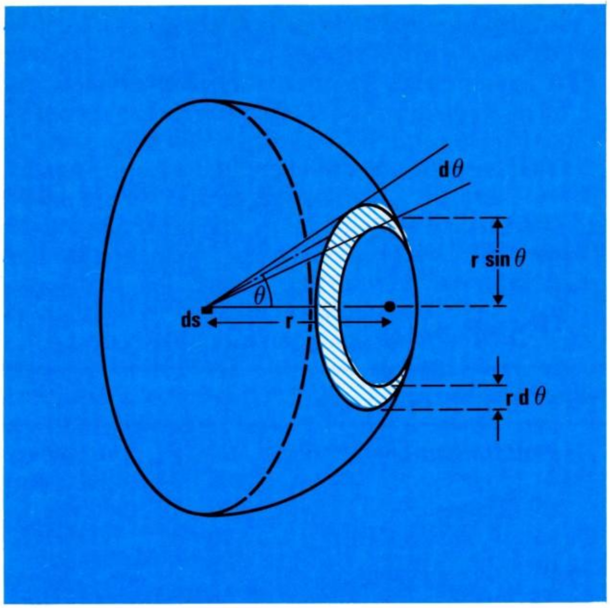


Fig. 2. The illumination of a hemisphere by a small element of a surface emitter.

The elemental luminous flux, $dF = I\omega = 2\pi L.ds.\cos\theta\sin\theta d\theta$

The flux emitted into the whole cone of semi-vertical angle θ

$$F = \int_0^\theta 2\pi L.ds.\cos\theta\sin\theta.d\theta$$
$$= \pi L.ds \sin^2\theta \text{ lumens}$$

When $\theta = 90°$, the total flux $F_t = \pi L.ds$ lumens
But this flux is also equal to E.ds lumens:

Therefore
$$\pi L.ds = E.ds$$
and hence
$$L = E/\pi$$

If the Lambertian surface absorbed some of the light, use can be made of the more general expression
$$L = E\beta/\pi$$
where β is the fraction of the light reflected (or transmitted) by the surface. If the surface is not Lambertian, this formula can still be used if β is evaluated as the fraction of the light reflected (or transmitted) by the surface in a specified direction relative to that reflected (or transmitted) by a non-absorbing Lambertain surface in the same direction. The formula $L = E\beta/\pi$ is very important; in Table I it has been used to calculate typical luminances.

A system of units is sometimes used based on the luminous flux in π steradians rather than in one steradian. Such units, denoted below by dashed symbols, are related to the units defined above by the equations:

$$I' = \pi I, \; L' = \pi L$$

Using these units the relationship between illuminance and luminance is simply $L' = E\beta$.

The name given to the unit for L' in this system is the 'apostilb':

$$1 \text{ apostilb} = 1/\pi \text{ cd/m}^2$$

However, the primary unit of luminance is the candela/m^2 (sometimes, in the past also called the *nit*). Other units of luminance incorporating the factor $1/\pi$ have also sometimes been used in the past, as shown in the footnote overleaf.

The following terms are also important in photometry.

Reflectance ρ
Ratio of the reflected to the incident luminous flux under specified conditions of illumination.

Transmittance τ
Ratio of the transmitted to the incident luminous flux under specified conditions of illumination.

Perfect Reflecting Diffuser
Ideal isotropic diffuser with a reflectance equal to unity.

Perfect Transmitting Diffuser
Ideal isotropic diffuser with a transmittance equal to unity.

Luminance Factor β
(at a representative surface element, in a given direction, under specified conditions of illumination).
Ratio of the luminance of the specimen considered to that of a perfect reflecting or transmitting diffuser identically illuminated. (Typical values of β are 0.93 for snow, 0.32 for soil, 0.01 for black velvet).

Reflectance Factor R
(at a representative surface element, under specified conditions of illumination).
Ratio of the luminous flux reflected by a surface

element within a specified cone to that reflected by a perfect reflecting diffuser within the same cone. (If the solid angle of the cone approaches a hemisphere, then the reflectance factor approaches the reflectance. If the solid angle of the cone approaches zero, then the reflectance factor approaches the luminance factor).

Luminous Exitance M
Luminous flux per unit area leaving a surface. Unit = lumen/m^2.

Luminous Efficacy
(a) Of a source. Ratio of luminous flux emitted to power consumed. Unit = lumen/Watt. Symbol = η.
(b) Of a radiation. Ratio of luminous flux to radiant flux. Unit = lumen/Watt. Symbol = K.

Luminous Efficiency V
Ratio of radiant flux, weighted according to the V(λ) function, to the radiant flux.

Light Exposure H
(at a point on a surface)
Quantity of light received per unit area. The unit is the lux-second.

Optical Density D
Logarithm to the base ten of the reciprocal of the reflectance or of the transmittance.

$$D = -\log_{10}\rho \qquad D = -\log_{10}\tau$$

When visual appearance is an important consideration, optical density is usually a more useful measure then reflectance or transmittance, because equal changes of density correspond more nearly to equally noticeable changes in the apparent lightness of specimens than is the case for reflectance or transmittance. The concept of optical density is also used in similar ways in connection with luminance factor and reflectance factor.

SPECTROPHOTOMETRY

In photometry the total visual effect of the light is considered. In spectrophotometry the amount of light at each wavelength is studied, and this is necessary when considering many colour phenomena. To measure the amount of light at each wavelength, it is necessary first to disperse the light into a spectrum, usually by means of a prism or a diffraction grating, and then to measure the amount of light at each wavelength with a photometer; hence the word spectrophotometry. The photometer may be used to measure the amount of light in absolute units, or relative to some standard emitter. For absolute work it is customary to measure radiant power rather than visible light, and the procedure is called spectroradiometry. The measurements can, of course, be converted from radiant power to light by using the V(λ) function. When the relative amount is measured, it is usual to do so by using a perfect reflecting or transmitting diffuser; the term *spectrophotometry* is usually confined to this relative procedure. We shall now consider the application of these procedures to sources, to reflecting samples, and to transmitting samples.

Sources
When measuring the radiant power produced by a source at each wavelength, if a detector is used that has equal sensitivity throughout the spectrum (such as a thermopile or a bolometer) then it is only necessary to correct for any non-uniformity of transmission throughout the spectrum by the dispersing device (and multiply by a calibration constant) to obtain the required readings. If a detector is used that does not have constant sensitivity throughout this spectrum (such as a photocell or a photo-sensitive diode) then this has to be corrected for in addition, with the aid of a spectral calibration curve for the detector used. Alternatively, the whole spectroradiometer can be calibrated by measuring not only the test radiation, but also that from a source whose spectral radiant power output is known. The *spectral radiant power*, P(λ) is then given by:

$$P(\lambda) = \frac{\text{Reading for Test Source at Wavelength } \lambda}{\text{Reading for Known Source at Wavelength } \lambda} P_0(\lambda)$$

where $P_0(\lambda)$ is the spectral radiant power of the known source at wavelength λ. In making these measurements on sources, it is important that the actual radiation of interest is measured, and this

Footnote: 1 Lambert = $10^4/\pi$ cd/m^2
1 milli-lambert = $10/\pi$ cd/m^2
1 foot-lambert = $1/\pi$ cd/ft^2
1 equivalent foot-candle = $1/\pi$ cd/ft^2

means that, if a source is used in a fitting that has some spectral non-uniformity, then the same fitting should be used when making the measurements. It may also be important to make the measurements on the radiation emitted in a particular direction, if there is any spectral variation with direction of emission. For these reasons, use is sometimes made of tele-spectroradiometers in which the radiation is picked up by a telescope which is directed at the point of interest on the source, and is located at the point of viewing interest. Tele-spectroradiometers are also sometimes used to study reflecting or transmitting samples, particularly when the illuminating and viewing conditions are complicated and the data is required to high accuracy in a particular practical situation.

Reflecting Samples

When a scene is illuminated by a source having some given spectral distribution, the observed colours of the various objects in view will depend upon the amount of light reflected from their surfaces at each wavelength throughout the spectrum.

Light may be reflected diffusely from a coloured surface, after partial absorption has modified its spectral composition, and it may be subject also to some degree of specular reflection, dependent upon the glossiness of the outer surface. Light reflected from the outer surface regions will be less affected by the pigmentation of the material than light that penetrates more deeply. If the surface is illuminated by white light, the reflected light will be a mixture of white light and light with some spectral components reduced in amplitude by absorption in the deeper regions. The resulting surface colour depends on the nature of the surface, the type of absorption, and the angles of viewing and illumination.

The light reflected from many surfaces encountered in practice (e.g. human skin) contains both specular and diffuse components. Its spectral distribution is different from that of the incident light, as a result of absorption in the pigmented surface regions. Reflection from coloured surfaces varies from wavelength to wavelength and any particular surface is said to have a *spectral reflectance factor* R(λ), defined as:

$$R(\lambda) = \frac{\text{light reflected into a cone at wavelength } \lambda}{\text{light reflected into the same cone by a perfect reflecting diffuser at wavelength } \lambda}$$

TABLE 2: THE CIE STANDARD CONDITIONS FOR SPECTROPHOTOMETRIC MEASUREMENTS

DESCRIPTION	SYMBOL	NOTES
	REFLECTING SAMPLES	
a) 45°/Normal	45/0	A, C_{10}, D_8, E_8
b) Normal/45°	0/45	A, B_{10}, D_8, E_8
c) Diffuse/Normal	d/0	C_{10}, D_5, E_5, F, H
d) Normal/Diffuse	0/d	B_{10}, D_5, F, H
	TRANSMITTING SAMPLES	
e) Normal/Normal	0/0	B_5, C_5, D_5, E_5, H, I
f) Normal/Diffuse	0/d	B_5, D_5, H
g) Diffuse/Normal	d/0	C_5, E_5, H
h) Diffuse/Diffuse	d/d	G

Notes to Table 2

A) The angles of 45° shall not have errors exceeding ±2°.
B_5) The angle between the axis of the illuminating beam and the normal to the surface shall not exceed 5°.
B_{10}) The angle between the axis of the illuminating beam and the normal to the surface shall not exceed 10°.
C_5) The angle between the axis of the viewing beam and the normal to the surface shall not exceed 5°.
C_{10}) The angle between the axis of the viewing beam and the normal to the surface shall not exceed 10°.
D_5) The divergence of the illuminating beam shall not exceed 5°.
D_8) The divergence of the illuminating beam shall not exceed 8°.
E_5) The divergence of the viewing beam shall not exceed 5°.
E_8) The divergence of the viewing beam shall not exceed 8°.
F) Any integrating sphere used shall be such that the total area of the ports does not exceed 10% of the internal reflecting area of the sphere.
G) Integrating spheres are to be used for illumination, and for the collection of the transmitted flux.
H) Any light traps used are to be described in detail.
I) The specimen is to be positioned so that only the regularly transmitted flux reaches the detector.

Because of the contributions of both specular and diffuse components to the light reflected from specimens, the results can be greatly affected by the geometry of the illuminating and viewing condition. The CIE has therefore specified several standard conditions under which such measurements should be made, on both reflecting and transmitting samples. They are summarised in Table 2 and its associated notes.

For the conditions 'diffuse/normal' and 'normal/diffuse' the regularly reflected component of specimens with specular and diffuse reflection may be excluded by the use of a gloss trap. If a gloss trap is used, details of its size, shape and position should be given.

Conditions (a), (b), (c), give values of reflectance factor, R(λ). For directional viewing with a sufficiently small angular spread, these reflectance factors become identical to luminance factors. Thus, in the limit, the 45/0 condition gives the luminance factor β45/0; the 0/45 condition gives the luminance

factor β0/45; the 'diffuse/normal' condition gives the luminance factor βd/O; and the 'normal/diffuse' condition gives the reflectance ρ.

Transmitting Samples

Spectrophotometry of transmitting samples, such as colour filters and films, is carried out in similar ways, the basic quantity measured by the *spectral transmittance*, τ(λ), is defined as:

$$\tau(\lambda) = \frac{\text{light transmitted at wavelength } \lambda}{\text{light incident at wavelength } \lambda}$$

Because, with many transmitting samples, both specular and diffuse components are present, the CIE recommends that spectrophotometry of transmitting specimens be carried out so as to correspond to one of the illuminating and viewing conditions given in Table 2.

Instruments designed to measure the densities of photographic films are usually designed to realise the normal/diffuse condition (without the use of a light trap), and the results are then commonly referred to as diffuse density; if the normal/normal or diffuse/diffuse conditions are realised the corresponding measures are referred to as specular density, or as double-diffuse density, respectively.

LIGHT SOURCES

The colours of objects can be greatly affected by the spectral composition of the light used to illuminate them: some of the more important types of sources will now be briefly reviewed.

Incandescence

The most familiar means of causing a substance to emit light is to raise it to a high temperature. As the temperature rises, the molecular activity increases and electromagnetic radiation of increasing power and higher frequency is produced. When a perfectly black body (i.e. one that absorbs all radiant energy falling upon it) is heated, the power radiated from a given area of its surface has a magnitude and spectral distribution determined solely by its temperature. At relatively low temperatures, most energy is radiated in the infra-red and red spectral regions. As the temperature is increased more and more radiation takes place at the shorter wavelengths and the colour changes from red to white and, eventually, to blue-white. The energy distributions of such radiators are expressed by Planck's law, which gives the spectral concentration of radiant exitance $M_{e\lambda}$, as follows:

$$M_{e\lambda} = C_1\lambda^{-5}(e^{C_2/\lambda T} - 1)^{-1} \text{ W.m}^{-3}$$

where
$$\left.\begin{aligned} C_1 &= 3.74183 \times 10^{-16} \text{ W.m}^2 \\ C_2 &= 1.4388 \times 10^{-2} \text{ m.K} \end{aligned}\right\} \text{radiation constants}$$
$$\lambda = \text{wavelength (m)}$$
$$T = \text{temperature (K)}$$

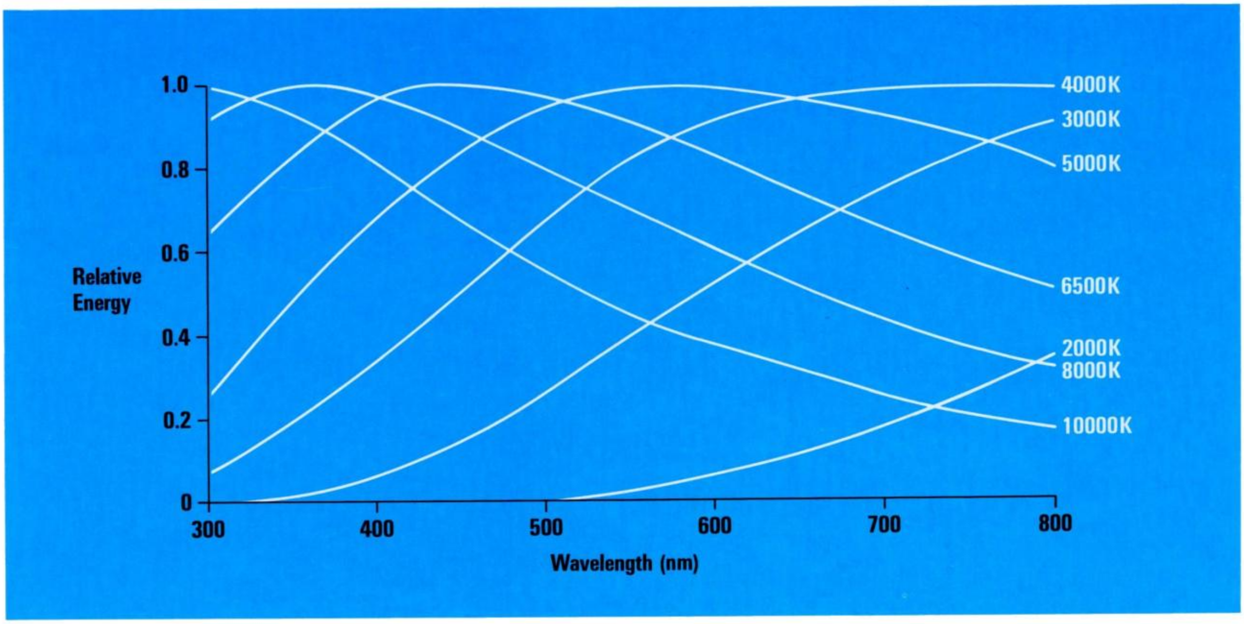


Fig. 3. The spectral power distribution of a Planckian radiator (normalised to output at $\lambda_{max} = 1.0$).

Figure 3 shows the relative spectral power distributions from such radiators, known as *Planckian radiators,* at a number of different temperatures. Although each curve extends from $\lambda = 0$ to $\lambda = \infty$, most of the power is concentrated in a relatively narrow region around a maximum value. The wavelength of this maximum is inversely proportional to the temperature, in accordance with the following relationship, which is known as Wein's Law.

$$\lambda_{max}T = 2.8978 \times 10^{-3} \text{ m deg K}$$

The level of radiant emittance has fallen to one percent of this maximum at wavelengths of approximately $0.33\lambda_{max}$ and $6.5\lambda_{max}$, independent of the temperature, T.

Artificial Light Sources

Artificial light sources fall into three main groups, in accordance with their spectral power content. The first group consists of sources that emit radiation by incandescence (e.g. candles, tungsten electric lamps). The second group consists of sources that emit radiant energy as the result of an electrical discharge through a gas or vapour (e.g. neon lamps, sodium vapour lamps, mercury vapour lamps). The third group consists of 'fluorescent tubes' in which a gas discharge emits visible or ultra violet radiation within the tube, and this causes phosphors on the inside surface of the tube to glow. Sources in the first group produce a continuous and smooth spectral distribution while those in the second and third groups produce a continuous distribution with superimposed energy of significant level in particular regions of the spectrum.

Figure 4a illustrates the spectral power distributions of some typical light sources.

Daylight

The most important light source of all is daylight, which consists of sunlight and skylight mixed in a great variety of ways, according to the solar altitude and weather conditions. Although the radiation from the surface of the sun is probably Planckian, by the time it has reached the surface of the earth, it has passed through the atmospheres of both the sun and the earth, and the resultant absorptions and scatterings produce spectral distributions that are markedly different from those of Planckian

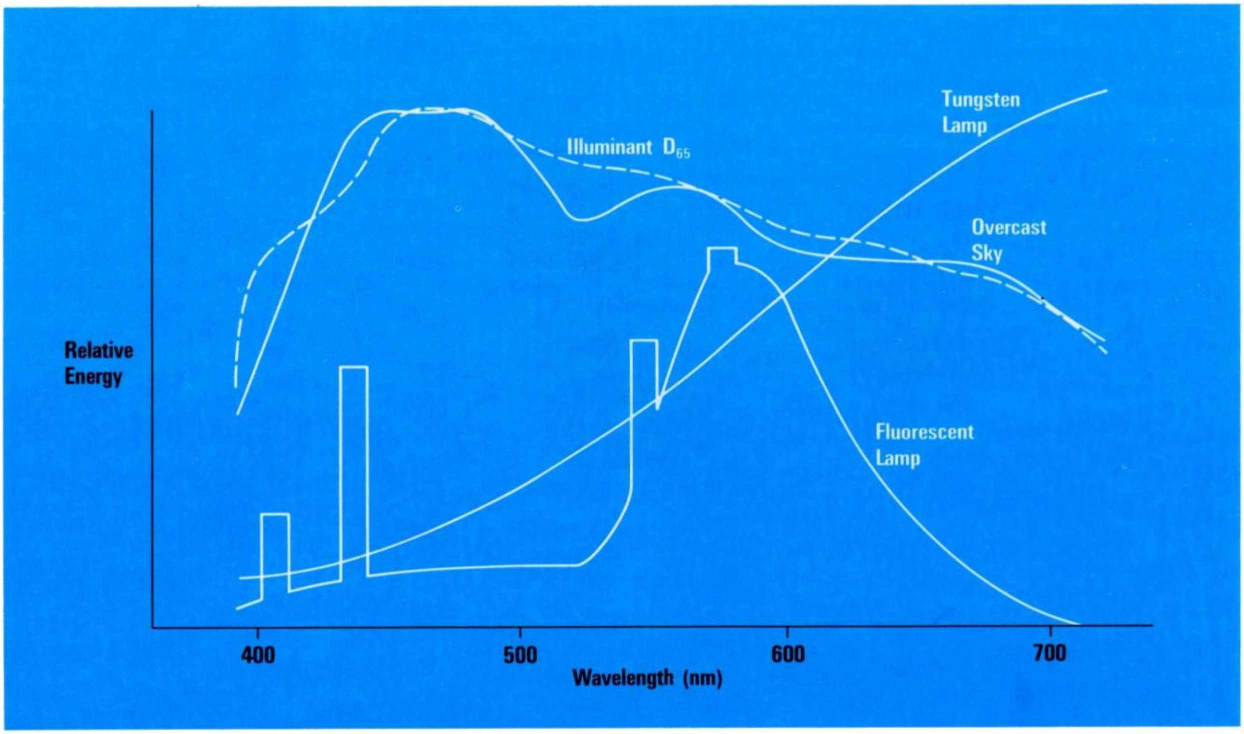


Fig. 4a. The spectral power distributions for four different sources of light.

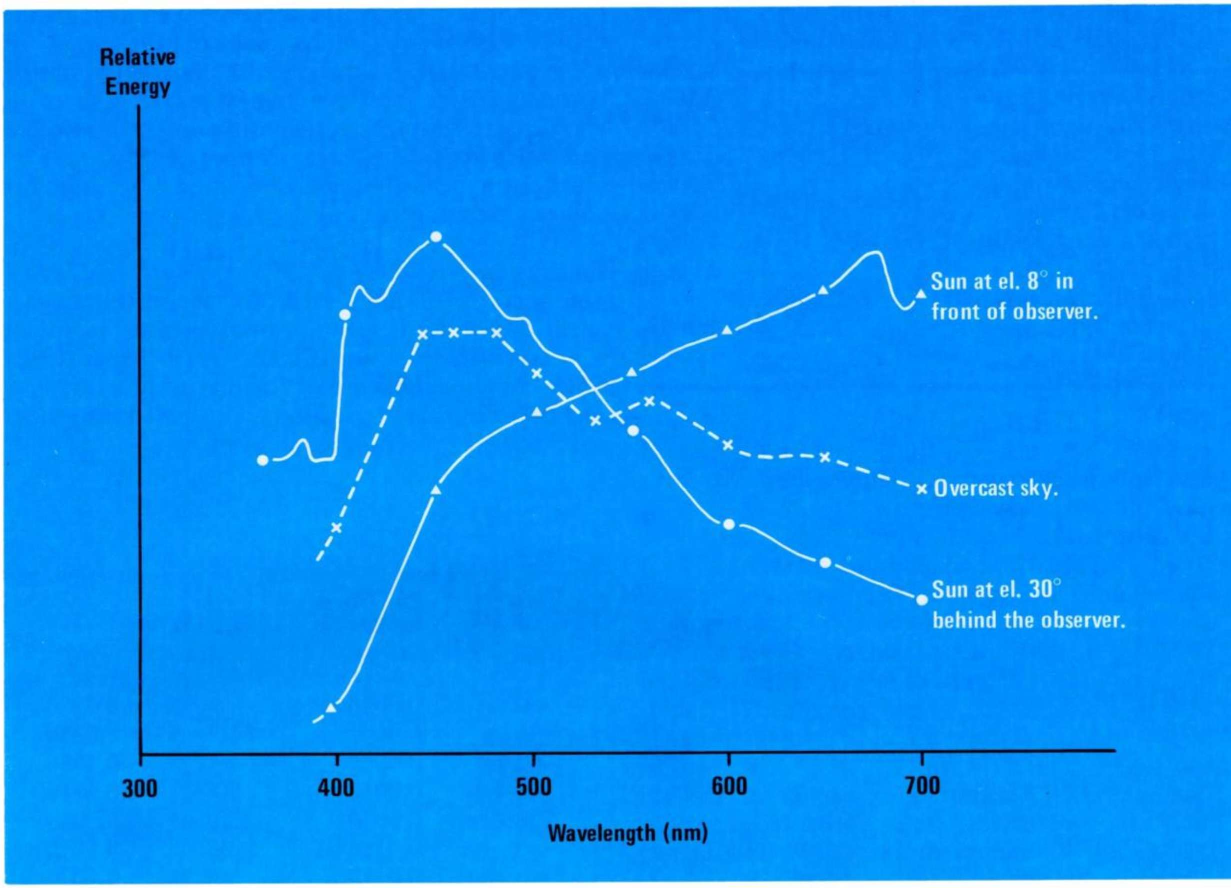


Fig. 4b. Smoothed spectral power distributions for typical daylight; a) from an overcast sky; b), with the sun at elevation 30° behind the observer; and c), with the sun at elevation 8° in front of the observer.

radiators. The law of scattering of sunlight by air molecules gives scattered energy proportional to $(\text{wavelength})^{-4}$. So scattered skylight is predominantly blue, while sunlight at morning and evening has lost most of its blue in the long air path and tends to be reddish. Typical spectra for three examples of daylight are shown in Fig. 4b.

Colour Temperature

An artificial light source of the incandescent type can be closely matched in colour by a Planckian radiator at a particular temperature and this is said to be the 'colour temperature' of the source. In general, the spectral distribution will not be identical with that produced by a Planckian radiator at the given temperature, even though the colour appears to be the same. In the case of incandescent radiators, these differences in spectral distribution are small. However, the spectra produced by discharge lamps and by daylight are considerably different from those of Planckian radiators and it is frequently impossible to achieve a close colour match at any temperature. In such cases, the light source can be given a 'correlated colour temperature', which is the temperature of the Planckian radiation yielding the closest possible colour match.

Some colour temperatures typical of sources often met with in practice are given in Table 3.

Standard Illuminants

The CIE defines a 'source' as a physical emitter of light, such as a lamp or the sun and sky. The term 'illuminant' refers to a specific spectral power distribution, not necessarily provided directly by a source, and not necessarily realisable.

TABLE 3: COLOUR TEMPERATURES TYPICAL OF SOME PRACTICAL SOURCES

North Sky Light	7,500K
Average Daylight	6,500K
Xenon (Arc or Flash)	6,000K
Sunlight plus Skylight	5,500K
Fluorescent Lamps	3,000K to 6,500K
Studio Tungsten Lamps	3,200K
Floodlights	3,000K
Domestic Tungsten Lamps	2,800K to 2,900K
Sunlight at Sunset	2,000K
Candle Flame	1,800K

The following standard illuminants have been defined for colorimetric purposes:

Illuminant A. Representing light from a Planckian radiator at 2856K.

Illuminant B. Representing direct sunlight with a correlated colour temperature of approximately 4874 K.

Illuminant C. Representing average daylight with a correlated colour temperature of approximately 6774 K.

Illuminant D_{65}. Representing a phase of daylight with a correlated colour temperature of approximately 6504 K.

Illuminant B is no longer in general use and Illuminants A and D_{65} suffice for most purposes. Illuminant A may be realised by a gas-filled tungsten filament lamp operating at a correlated colour temperature of 2856 K. The spectral power distributions of CIE Standard Illuminants A and D_{65} are tabulated at 5nm intervals in Appendix B.

Each of the standard illuminants mentioned above has a power distribution that varies from wavelength to wavelength throughout the visible spectrum. In non-scientific terms, they each produce a different form of 'white' light. The choice of white is of fundamental importance in colour specification and the CIE makes use of the theoretical concept of the equi-energy illuminant as one of the bases of colorimetry. The equi-energy illuminant has a constant power level per unit of wavelength at all wavelengths throughout the visible spectrum. Such a spectral power distribution cannot be produced by any known means, but this does not detract from the value of the concept.

Conclusion

The photometric units used, and the measurements taken are of fundamental importance to engineers who work in television studios, or in departments which monitor the technical quality of programmes. The following chapters assume a knowledge of these units and methods of measurement.

APPENDIX A

The CIE photopic spectral luminous efficiency function.

λ(nm)	V(λ)	λ(nm)	V(λ)
380	0.0000	590	0.7570
90	0.0001	600	0.6310
400	0.0004	10	0.5030
10	0.0012	20	0.3810
20	0.0040	30	0.2650
30	0.0116	40	0.1750
40	0.0230	50	0.1070
50	0.0380	60	0.0610
60	0.0600	70	0.0320
70	0.0910	80	0.0170
80	0.1390	90	0.0082
90	0.2080	700	0.0041
500	0.3230	10	0.0021
10	0.5030	20	0.0010
20	0.7100	30	0.0005
30	0.8620	40	0.0002
40	0.9540	50	0.0001
50	0.9950	60	0.0001
60	0.9950	70	0.0000
70	0.9520	780	0.0000
580	0.8700		

APPENDIX B

The spectral power distributions of CIE Standard Illuminants A and D_{65}

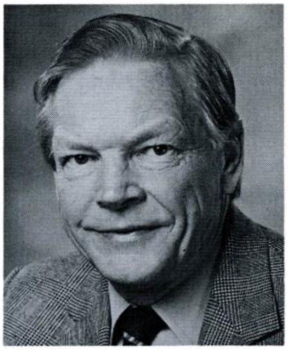
λ(nm)	A	D_{65}	λ(nm)	A	D_{65}	λ(nm)	A	D_{65}
380	9.80	49.98	515	69.25	106.30	650	165.03	80.03
85	10.90	52.31	20	72.50	104.79	55	168.51	80.12
90	12.09	54.65	25	75.79	106.24	60	171.96	80.21
95	13.35	68.70	30	79.13	107.69	65	175.38	81.25
400	14.71	82.75	35	82.52	106.05	70	178.77	82.28
5	16.51	87.12	40	85.95	104.41	75	182.12	80.28
10	17.68	91.49	45	89.41	104.23	80	185.43	78.28
15	19.29	92.46	50	92.91	104.05	85	188.70	74.00
20	20.99	93.43	55	96.44	102.02	90	191.93	69.72
25	22.79	90.06	60	100.00	100.00	95	195.12	70.67
30	24.67	86.68	65	103.58	98.17	700	198.26	71.61
35	26.64	95.77	70	107.18	96.33	5	201.36	72.98
40	28.70	104.86	75	110.80	96.06	10	204.41	74.35
45	30.85	110.94	80	114.44	95.79	15	207.41	67.98
50	33.09	117.01	85	118.08	92.24	20	210.36	61.60
55	35.41	117.41	90	121.73	88.69	25	213.27	65.74
60	37.81	117.81	95	125.39	89.35	30	216.12	69.89
65	40.30	116.34	600	129.04	90.01	35	218.92	72.49
70	42.87	114.86	5	132.70	89.80	40	221.67	75.09
75	45.52	115.39	10	136.35	89.60	45	224.36	69.30
80	48.24	115.92	15	139.99	88.65	50	227.00	63.59
85	51.04	112.37	20	143.62	87.70	55	229.59	55.00
90	53.91	108.81	25	147.24	85.49	60	232.12	46.40
95	56.85	109.08	30	150.84	83.29	65	234.59	56.61
500	59.86	109.35	35	154.42	83.49	70	237.01	66.80
5	62.93	108.58	40	157.98	83.70	75	239.37	65.09
510	66.06	107.80	645	161.52	81.86	780	241.68	63.38

Chromaticity co-ordinates

A $x = 0.4476$ $y = 0.4074$ $u' = 0.2560$ $v' = 0.5243$

D_{65} $x = 0.3127$ $y = 0.3290$ $u' = 0.1978$ $v' = 0.4683$

ROBERT W. G. HUNT,
B.Sc., Ph.D., D.Sc.
A biographical note appears on page 4.



Synopsis

Colorimetry is based on the fact that observers can match colours with additive mixtures of three reference stimuli, in amounts known as tristimulus values. Using reference stimuli at specified wavelengths, the CIE has defined a standard set of tristimulus values to match each different wavelength of the spectrum and this data constitutes the standard '1931 colorimetric observer'. To avoid negative tristimulus values, a new set of colour matching functions was derived from the standard data, in terms of imaginary primaries X, Y and Z. The proportions of the primaries used in a colour match are known as chromaticity co-ordinates which may be plotted on a chromaticity diagram or colour map. To obtain a diagram which provides a reasonably uniform scale in relation to perceived colour changes, the 1976 CIELUV system has been introduced, using modified axes known as u′ and v′. Colour difference formulae must take account of luminance as well as chromaticity and thus they require three dimensions. The CIE has recommended two colour spaces for the evaluation of perceptually important colour attributes.

Colorimetry

by Prof. R. W. G. Hunt

INTRODUCTION

The most fundamental physical measurement of a colour stimulus is its spectral radiant power, P(λ). But the practical utility of this measurement is limited by two facts: first, stimuli having quite different spectral radiant power functions can appear to be identical in colour; secondly, spectral radiant power functions do not correlate in any simple way with the usual attributes of colour appearance, such as hue, brightness, and colourfulness. In colorimetry, the evaluation of tristimulus values identifies that colours match one another; and the derivation from these of measures that are correlated with perceptual colour attributes can be used to indicate the appearance of colours when viewed in specified conditions.

Trichromacy

Colorimetry is based on the experimental fact that observers can match colours with additive mixtures of three reference-colour stimuli, normally a red, a green and a blue. The reason that this is possible is that, in colour vision, the retina of the human eye transduces the incident radiant power of the light to electrical signals, by means of only three spectrally different types of receptor, known as cones. There is a fourth spectrally different type of receptor, known as a rod, but the rods give only monochrome vision at low levels of illuminance. At levels high enough for colour perception to be operating effectively, it can be assumed, for the purposes of practical colorimetry, that the rods are inhibited by the cones and are inoperative. In Fig. 1, spectral sensitivity curves typical of those believed to be characteristic of the cones are shown.

It is clear that one type of cone has a peak sensitivity at about 580nm, another at about 540nm, and the third at about 440nm; hence, red light stimulates mainly the first type of cone, green light mainly the second type, and blue light mainly the third type. Therefore, if beams of red, green and blue light can be varied in their amounts, and additively mixed together, the combination can be made to

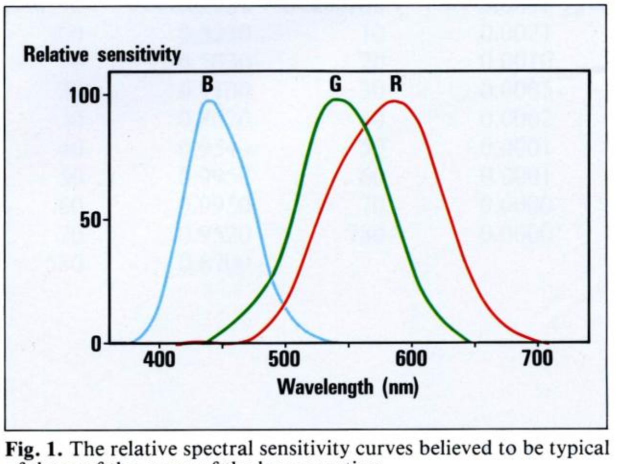


Fig. 1. The relative spectral sensitivity curves believed to be typical of those of the cones of the human retina.

produce a very wide range of excitations of the three different types of cone; by adjusting the amounts until the cone excitations are the same as those produced by another colour stimulus, a match can be made. The amounts of the red, green, and blue needed to make the match can then serve as a measure of the colour of the other stimulus, and these amounts are known as *tristimulus values.* If yet another colour stimulus, having a different spectral radiant power distribution, was also matched, different tristimulus values would indicate that the colour looked different, while identical tristimulus values would indicate that it looked the same. Colours having identical tristimulus values but different spectral radiant power distributions are called *metamers,* and the phenomenon *metamerism.* The greater the difference in spectral radiant power distribution between two matching colours, the greater is said to be the degree of metamerism.

The CIE 1931 Standard Observer

For tristimulus values to provide a satisfactory basis for the measurement of colour, it is necessary to standardise various elements of the system.

In the first place, not surprisingly, if the colours of the red, green, and blue reference-colour stimuli are changed, even slightly, the tristimulus values for a given stimulus being matched will also change. Secondly, it is found that, even if observers having abnormal colour vision ('colour blind' observers) are excluded, individual observers differ slightly from one another in their tristimulus values for a match; a phenomenon often referred to as *observer metamerism.* Thirdly, it is found that the angular size of the field of view affects the colour match.

The CIE has therefore defined a standard set of reference-colour stimuli, and a standard set of tristimulus values for them to match the wavelengths of the spectrum; this data constitutes the *CIE 1931 standard colorimetric observer.* The reference-colour stimuli are monochromatic radiations of wavelength 700nm for the red stimulus (R), 546.1nm for the green stimulus (G), and 435.8nm for the blue stimulus (B). The units to be used for measuring the amounts of the three reference-colour stimuli now must be considered. If a typical white colour is matched, and the amounts are measured in photometric units, such as lumens, or candelas per square metre, it is found that, with any reasonably typical set of red, green, and blue reference-colour stimuli, there is a great imbalance in the three amounts, the amount of green being the greatest, and the amount of blue being much smaller. Thus, with the three CIE reference-colour stimuli, R, G, B, it is

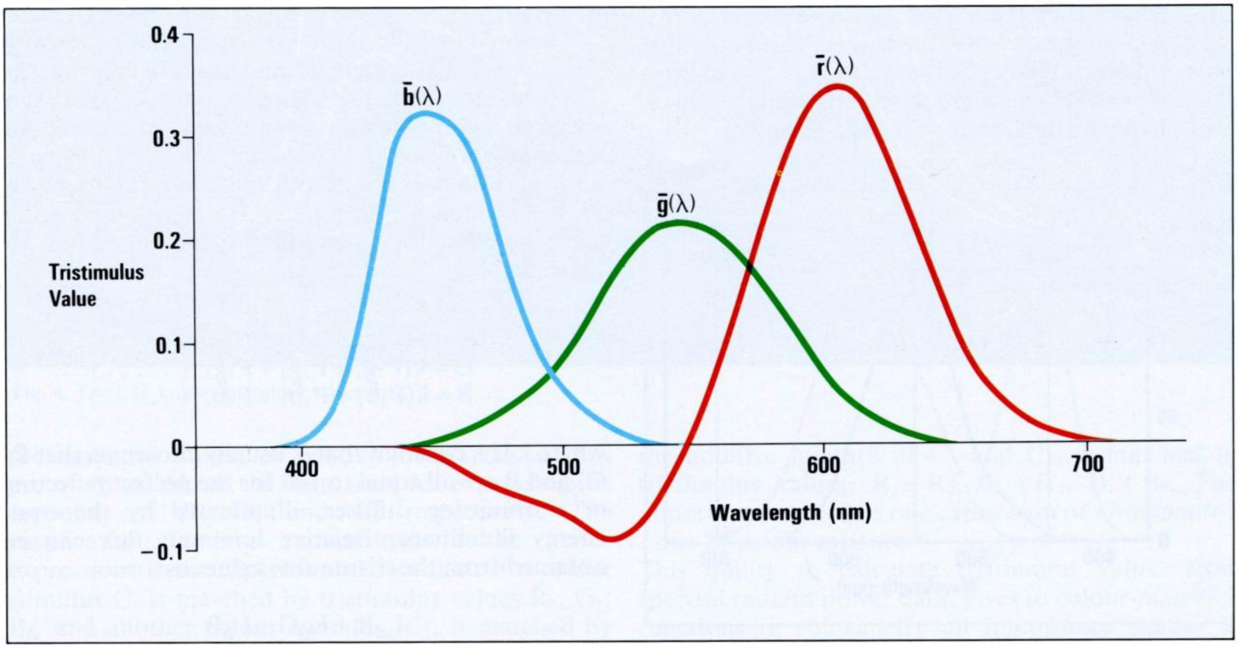


Fig. 2. Colour matching functions.

found that 5.6508 lumens of the equi-energy illuminant is matched by:

1.0000 lumen of R
4.5907 lumens of G
0.0601 lumens of B

But the equi-energy illuminant generally has a whitish appearance, and, perceptually, white is a colour that is not biassed towards either red, green, or blue; hence, it is desirable for a colorimetric system to be arranged so that white is matched by equal quantities of the three reference-colour stimuli. This is easily achieved by using units of different photometric magnitudes for each of the three reference-colour stimuli. Thus, if 1.0000 lumen was still used for R, but 4.5907 lumens for G, and 0.0601 lumens for B, then 5.6508 lumens of the equi-energy illuminant would be matched by:

1.0000 lumen of R
1.0000 new unit of G
1.0000 new unit of B

This is what is done in the CIE system, and in Fig. 2 the amounts of R, G, and B, measured in these new units are shown for each wavelength of the spectrum.

It is clear from Fig. 2 that, at some wavelengths, one of the three amounts is negative. This is because some colours cannot be matched by an additive mixture of the three reference-colour stimuli. This is most obviously the case for the blue-green part of the

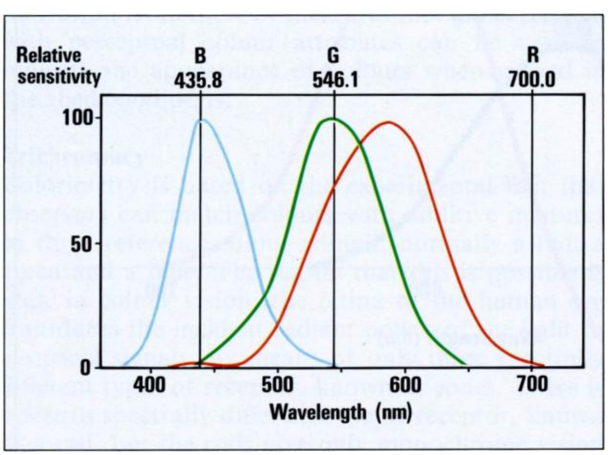


Fig. 3. The cone spectral sensitivity curves for Fig. 1 with the wavelengths of the CIE RGB primaries.

spectrum around 500nm. The reason for this can be seen by referring to Fig. 3, where the wavelengths of the reference-colour stimuli are shown on the cone spectral-sensitivity curves of Fig. 1. It is clear that the R stimulus will excite only the cones whose peak sensitivity is at about 580nm (the 580-cones); and the B stimulus will excite mainly the 440-cones; but the G stimulus, although exciting the 540-cones most strongly, also excites the 580-cones to a considerable extent. At 500nm, the cone excitations are approximately in the ratios of 1 of 580 to 2 of 540 to 1 of 440. But the G stimulus excites the cones in the ratio of about 1 of 580 to 2 of 540. So that, when trying to match the blue-green of 500nm, even without any R present, the G stimulus produces too high a ratio of 580-cone to 540-cone stimulation. The only way to make a match is therefore to add some R stimulus to the 500nm colour, so that this combination then produces a higher ratio of 580-cone response to 540-cone response. By adding just the right amount of R stimulus to the 500nm colour, it is found that a match can then be made by adjusting the amounts of the G and B stimuli appropriately. When this is done, the amount of R in the match is counted as negative. This problem of unmatchable colours occurs (although to different extents) with all sets of reference-colour stimuli, and is caused by the degree of overlap of the three curves of Fig. 1.

The curves of Fig. 2 are known as *colour-matching functions* and are of great importance in colorimetry. They enable tristimulus values to be calculated from spectral radiant power distributions. If the radiant fluxes at wavelengths 1, 2, 3, etc., are P_1, P_2, P_3, etc., and the values of the colour matching functions are $\bar{r}_1$, $\bar{r}_2$, $\bar{r}_3$, etc., $\bar{g}_1$, $\bar{g}_2$, $\bar{g}_3$, etc., $\bar{b}_1$, $\bar{b}_2$, $\bar{b}_3$, etc., at the same wavelengths, then the tristimulus values are given by:

$$R = k(P_1\bar{r}_1 + P_2\bar{r}_2 + P_3\bar{r}_3 + \ldots\ldots)$$
$$G = k(P_1\bar{g}_1 + P_2\bar{g}_2 + P_3\bar{g}_3 + \ldots\ldots)$$
$$B = k(P_1\bar{b}_1 + P_2\bar{b}_2 + P_3\bar{b}_3 + \ldots\ldots)$$

where k is a constant that is usually chosen so that R, G, and B are all equal to 100 for the perfect reflecting or transmitting diffuser, illuminated by the equi-energy illuminant. Relative luminous flux can be obtained from the tristimulus values as:

$$L_R R + L_G G + L_B B$$

where $L_R = 1.0000$, $L_G = 4.5907$, $L_B = 0.0601$, being

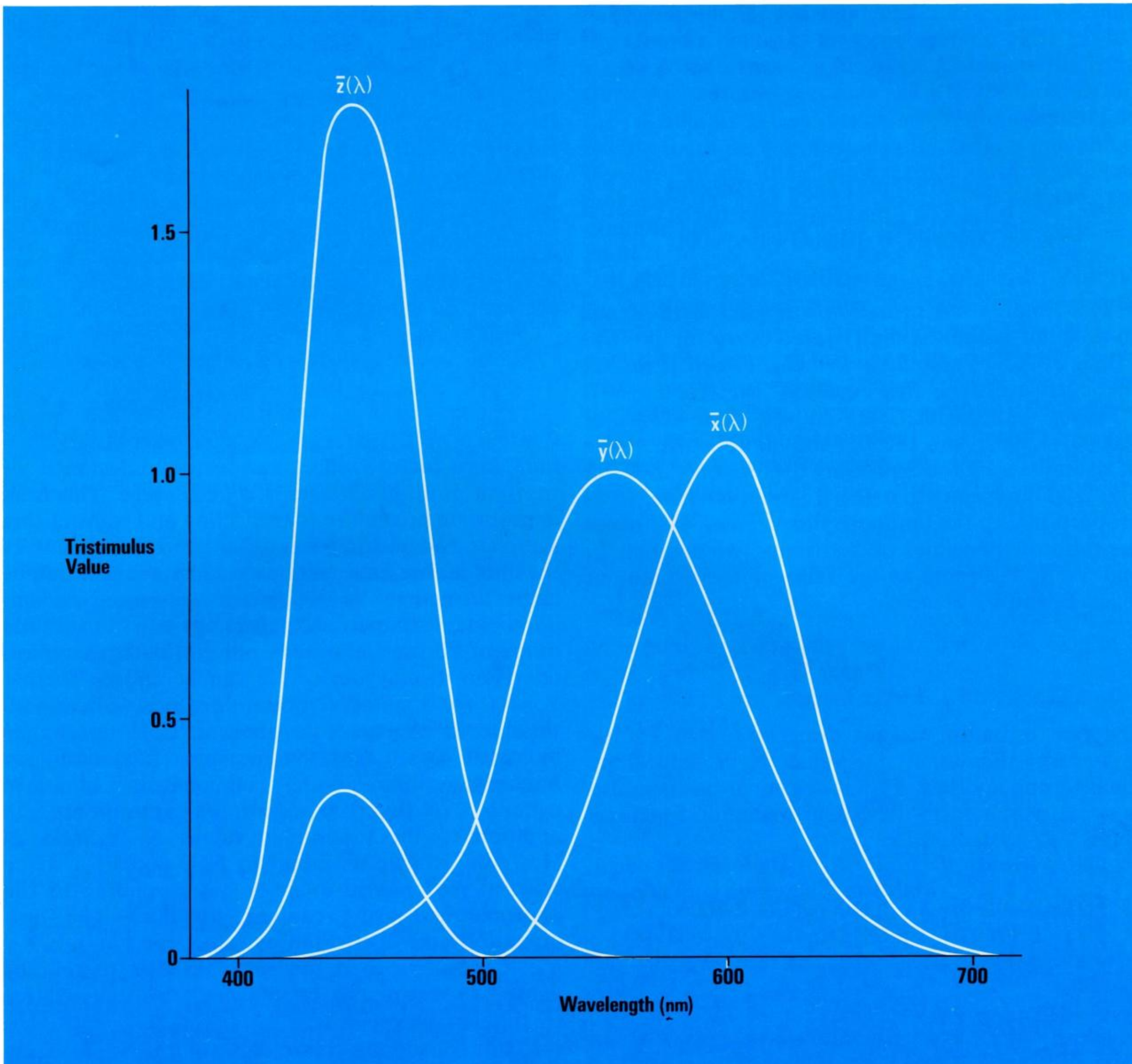


Fig. 4. The CIE colour-matching functions.

the luminous fluxes, or relative luminances as they are often called, of the units used for expressing the amounts of R, G, and B, respectively. The justification for the summations in the above expressions is the experimental fact that, if a colour stimulus C_1 is matched by tristimulus values R_1, G_1, B_1, and another colour stimulus, C_2, is matched by tristimulus values (using the same reference-colour stimuli measured in the same units), R_2, G_2, B_2, then the additive mixture of C_1 and C_2, is matched by tristimulus values, R_1+R_2, G_1+G_2, B_1+B_2. This important property is one expression of *Grassmann's Laws* of colour mixture.

This ability to calculate tristimulus values from spectral radiant power data, gives to colour-matching functions in colorimetry an importance similar to that of the $V(\lambda)$ function in photometry.

The inevitable presence of negative tristimulus

values in red, green, blue, systems of colorimetry has led the CIE to adopt a system in which a new set of tristimulus values, X, Y, Z, is used. X, Y, Z are obtained from R, G, B by using the following equations:

$$X = 0.49000R + 0.31000G + 0.20000B$$
$$Y = 0.17697R + 0.81240G + 0.01063B$$
$$Z = 0.00000R + 0.01000G + 0.99000B$$

This simple transformation was carefully designed so that all colour stimuli would have all positive values of X, Y, and Z. It was also designed so that the coefficients in the equation for Y, 0.17697, 0.81240, and 0.01063, are in the same ratios as 1.0000, 4.5907, and 0.0601, the photometric values of the units used for expressing the amounts of R, G, and B. This means that the tristimulus value, Y, is proportional to the luminous flux present, and hence the ratio of the values of Y for any two colours, Y_1 and Y_2, is the same as the ratio of their luminous fluxes F_1 and F_2. Hence:

$$Y_1/Y_2 = F_1/F_2$$

The transformation was also designed so that, for the equi-energy illuminant, the values X, Y, and Z are equal to one another. The above equations can also be used to transform the colour-matching functions to the XYZ system, thus:

$$\bar{x}(\lambda) = 0.49000\bar{r}(\lambda) + 0.31000\bar{g}(\lambda) + 0.20000\bar{b}(\lambda)$$
$$\bar{y}(\lambda) = 0.17697\bar{r}(\lambda) + 0.81240\bar{g}(\lambda) + 0.01063\bar{b}(\lambda)$$
$$\bar{z}(\lambda) = 0.00000\bar{r}(\lambda) + 0.01000\bar{g}(\lambda) + 0.99000\bar{b}(\lambda)$$

These colour matching functions x(λ), y(λ), z(λ), are shown in Fig. 4 and are the most important spectral functions in colorimetry. They enable tristimulus values X, Y, Z to be calculated directly from spectral radiant power data. If the radiant fluxes at wavelengths 1, 2, 3, etc., are P_1, P_2, P_3, etc. And the values of these colour-matching functions are $\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$, etc., $\bar{y}_1$, $\bar{y}_2$, $\bar{y}_3$, etc., and $\bar{z}_1$, $\bar{z}_2$, $\bar{z}_3$, etc., at the same wavelengths, then the tristimulus values are given by:

$$X = k(P_1\bar{x}_1 + P_2\bar{x}_2 + P_3\bar{x}_3 + \ldots\ldots)$$
$$Y = k(P_1\bar{y}_1 + P_2\bar{y}_2 + P_3\bar{y}_3 + \ldots\ldots)$$
$$Z = k(P_1\bar{z}_1 + P_2\bar{z}_2 + P_3\bar{z}_3 + \ldots\ldots)$$

where k is, again, a constant, whose value will be discussed later.

It is clear that, because the summation for Y yields values proportional to luminous flux, the shape of the $\bar{y}(\lambda)$ function must be the same as that of the V(λ) function, apart from a possible multiplying factor that is constant throughout the spectrum. In fact the transformation equations have been chosen so that the $\bar{y}(\lambda)$ and V(λ) functions are identical, both having a value of 1.0000 at 555nm. This means that the CIE XYZ system of colorimetry involves only two spectral functions, $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$, in addition to the V(λ) function used in photometry.

The constant, k, is usually chosen so that X, Y and Z, are all equal to 100 for the perfect reflecting or transmitting diffuser, illuminated by the equi-energy illuminant. The values of Y then usually give the luminance factor, reflectance factor, reflectance, or transmittance, in all cases as a percentage. This is an appropriate procedure for reflecting and transmitting samples, and yields results that are independent of the illuminance on the samples. For sources, k can be chosen so that Y = 100 when they are used to illuminate the perfect reflecting or transmitting diffuser. For self-luminous objects, such as typical television display devices, k can be chosen so that Y = 100 for a suitably chosen reference white. In all these cases the absolute photometric level can be indicated by quoting the luminous flux, luminous intensity, illuminance, luminance, luminous exitance, or light exposure, as appropriate, in addition to the tristimulus values X, Y, and Z. However, if k is set equal to 683, and P(λ) is the spectral radiometric quantity corresponding to the photometric measure required, then this will be given directly by the Y tristimulus value; the symbols X_a, Y_a, Z_a, can be used for such absolute tristimulus values, to distinguish them from the usual relative tristimulus values, X,Y,Z.

When calculating tristimulus values, X, Y, Z, or X_a, Y_a, Z_a, the summations are usually carried out at 5nm intervals, but intervals of 1, 10 or 20nm are sometimes used instead. A table of values of $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ at 5nm intervals is given in an Appendix to this chapter.

The CIE 1964 Observer

As mentioned earlier, colour matches are affected by the angular subtense of the field of observation, and the CIE has also standardised a set of colour-matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ for fields of view in excess of about 4°; they constitute the *CIE*

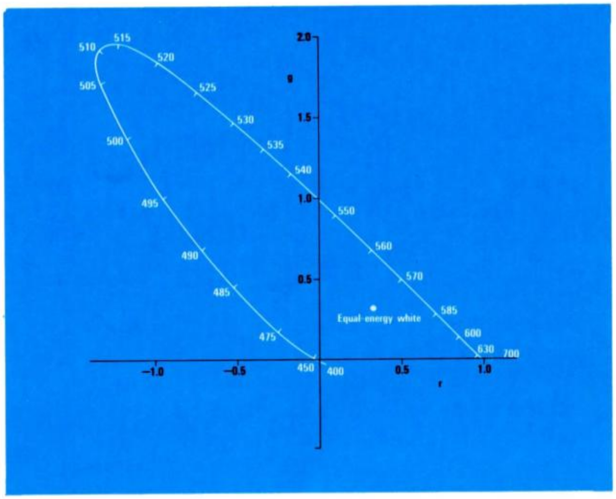


Fig. 5. The CIE r,g chromaticity diagram (wavelengths in nm).

1964 supplementary standard colorimetric observer. In television applications, the areas of colours of interest in displays usually have angular subtenses less then 4° and the CIE 1931 standard colorimetric observer is therefore the appropriate one to use.

Chromaticity Co-ordinates

Important colour properties are related to the *relative* magnitudes of tristimulus values. It is therefore useful to calculate *chromaticity co-ordinates,* and this can be done in both the RGB and XYZ systems as follows:

$$r = R/(R+G+B) \qquad x = X/(X+Y+Z)$$
$$g = G/(R+G+B) \qquad y = Y/(X+Y+Z)$$
$$b = B/(R+G+B) \qquad z = Z/(X+Y+Z)$$

Since $r+g+b=1$, if r and g are known, b can be deduced from 1-r-g. Similarly, z can be deduced from 1-x-y. It is therefore convenient to plot, in two-dimensional diagrams, either g against r, or y against x, as shown in Figs. 5 and 6; these are called *chromaticity diagrams,* and provide "maps" of colours. In Fig. 5, the equi-energy illuminant, for which $R=G=B$, plots at $r=1/3$, $g=1/3$. If for some other colour, for example, $R=8$, $G=48$, $B=24$; then $r=0.1$, $g=0.6$, $b=0.3$. This indicates that, in the colour match, there was 10% of the red, 60% of the green, and 30% of the blue, and that the colour is therefore a bluish green. In Fig. 5, the positions of the colours of the spectrum (the *spectrum locus*) are shown by the curved line, and the negative values of r are evident for the blue-green spectral colours.

The points representing pale colours plot between the illuminant point and the spectrum locus, and purple colours between the two ends of the spectrum. Chromaticity diagrams only show the *proportions* of the tristimulus values; hence bright and dim colours having the same proportions plot at the same point. For this reason, the illuminant point also represents grey colours; and orange and brown colours, for example, tend to plot at similar positions to one another.

If in a chromaticity diagram, a colour, C_1, plots at r_1, g_1, and another colour, C_2, plots at r_2, g_2, the position of C_3, the additive mixture of C_1 and C_2, is such that it lies on the straight line joining the points r_1, g_1, and r_2, g_2, as shown in Fig. 7. The co-ordinates, r_3, g_3, representing C_3, can be calculated as follows. If the luminous fluxes of C_1 and C_2 in the mixture are F_1 and F_2 respectively, then:

The additive mixture of r_1 of R with g_1 of G and b_1 of B represents

$$L_R r_1 + L_G g_1 + L_B b_1 = L_1 \text{ lumens}$$

where L_R, L_G, L_B, are the luminous fluxes of the units used for expressing the amounts of R, G, and B respectively.

The additive mixture of r_2 of R with g_2 of G and b_2 of B represents

$$L_R r_2 + L_G g_2 + L_B b_2 = L_2 \text{ lumens}$$

Hence the amounts of R, G and B needed to match the following stimuli are as follows:

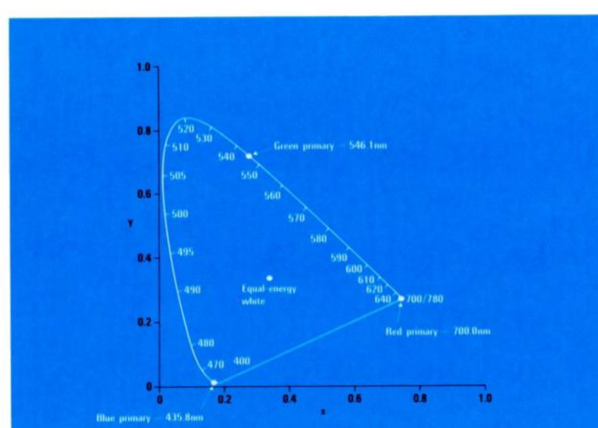


Fig. 6. The CIE x, y chromaticity diagram.

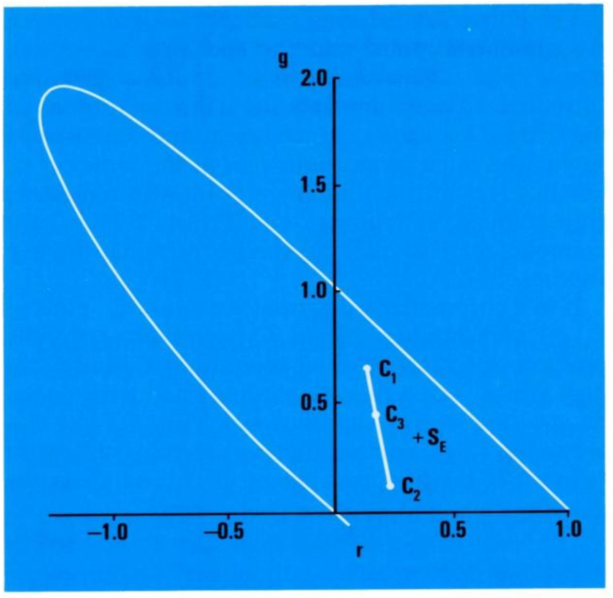


Fig. 7. The CIE r, g chromaticity diagram showing an example of the additive mixing of the colours C_1 and C_2.

Stimulus	R	G	B
1 lumen of C_1	$=\frac{1}{L_1}r_1$	$+\frac{1}{L_1}g_1$	$+\frac{1}{L_1}b_1$
F_1 lumens of C_1	$=\frac{F_1}{L_1}r_1$	$+\frac{F_1}{L_1}g_1$	$+\frac{F_1}{L_1}b_1$
F_2 lumens of C_2	$=\frac{F_2}{L_2}r_2$	$+\frac{F_2}{L_2}g_2$	$+\frac{F_2}{L_2}r_2$

F_1+F_2 lumens of C_3 =

$$\frac{F_1}{L_1}r_1+\frac{F_2}{L_2}r_2+\frac{F_1}{L_1}g_1+\frac{F_2}{L_2}g_2+\frac{F_1}{L_1}b_1+\frac{F_2}{L_2}b_2$$

Because $r_1+g_1+b_1=1$ and $r_2+g_2+b_2=1$, it follows that

$$\frac{F_1}{L_1}r_1+\frac{F_2}{L_2}r_1+\frac{F_1}{L_1}g_1+\frac{F_2}{L_2}g_2+\frac{F_1}{L_1}b_1+\frac{F_2}{L_2}b_2=\frac{F_1}{L_1}+\frac{F_2}{L_2}$$

Hence the chromaticity co-ordinates, r_3, g_3, representing C_3, are given by:

$$r_3=\left(\frac{F_1}{L_1}r_1+\frac{F_2}{L_2}r_2\right)\Big/\left(\frac{F_1}{L_1}+\frac{F_2}{L_2}\right)$$

$$g_3=\left(\frac{F_1}{L_1}g_1+\frac{F_2}{L_2}g_2\right)\Big/\left(\frac{F_1}{L_1}+\frac{F_2}{L_2}\right)$$

This is the formula for a point, r_3, g_3, on the straight line joining r_1, g_1 to r_2 g_2 and dividing it in the inverse ratio $(F_2/L_2)/(F_1/L_1)$. Thus the greater F_2/L_2 relative to F_1/L_1, the nearer the point representing C_3 lies to that representing C_2, and vice versa. The condition for the point representing C_3 to be mid-way between those representing C_1 and C_2 is not $F_1=F_2$, but $F_1/L_1=F_2/L_2$.

All the above considerations apply equally to the x, y chromaticity diagram shown in Fig. 6. However, in this case, the luminous fluxes are proportional to Y, so that:

$$L_1=L_Y y_1$$
$$L_2=L_Y y_2$$

Where L_Y is the relative luminance of the unit used for expressing the amount, Y. Although these values of L_1 and L_2 can be used to determine x_3 and y_3, the same result is obtained if y_1 and y_2 are used instead of $L_Y y_1$ and $L_Y y_2$. The formulae for x_3 and y_3 therefore simplify to:

$$x_3=\left(\frac{F_1}{y_1}x_1+\frac{F_2}{y_2}x_2\right)\Big/\left(\frac{F_1}{y_1}+\frac{F_2}{y_2}\right)$$

$$y_3=(F_1+F_2)\Big/\left(\frac{F_1}{y_1}+\frac{F_2}{y_2}\right)$$

The point representing C_3 then divides the line joining the points representing C_1 and C_2 in the inverse ratio $(F_2/y_2)/(F_1/y_1)$.

It is clear from Fig. 6 that the spectral colours are all represented by positive values of x and y (and z is also always positive). And because mixtures of colours are always represented by points lying along the straight line joining the points representing their components, all mixtures of spectral colours must always be located within the spectral locus, since it has no concavities on its outer side. Hence no colour can ever fall outside the spectral locus, and thus no colour can ever require negative values of x or y; and z can never be negative, since $x+y$ never exceeds unity.

In Fig. 8 are illustrated the derivations of two measures that correlate more closely with perceptual attributes of colours than tristimulus values or chromaticity coordinates. The point C represents the

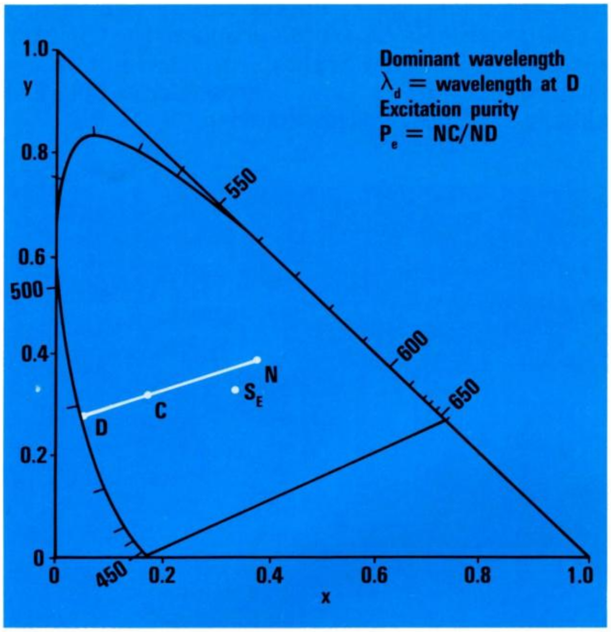


Fig. 8. The evaluation, in the x, y diagram, of dominant wavelength and excitation purity.

chromaticities of the colour being considered; the point, N, that of a suitably chosen reference white or grey (usually the chromaticity of the illuminant, but this is normally different from the equi-energy illuminant, S_E); and the point, D, that lies on the spectral locus intersected by the line NC produced. The wavelength corresponding to the point D is then termed the *dominant wavelength*, λ_d (if the point D lies on the line joining the two ends of the spectrum, then it is produced in the other direction to give the complementary wavelength, λ_c). Dominant wavelength provides a measure that correlates approximately with *hue*. The ratio NC/ND is termed the *excitation purity*, p_e, and correlates approximately with *saturation* (colourfulness judged in proportion to brightness). If, for reflecting or transmitting factors, *luminance factor*, which correlates with lightness, is also evaluated, then dominant wavelength, excitation purity, and luminance factor, together provide correlates of hue, saturation and lightness, respectively.

Uniform Chromaticity Diagrams

Chromaticity diagrams are very useful in colorimetry, but although the CIE x, y diagram has been widely used in the past, it does suffer from one important disadvantage.

In Fig. 9, are shown distances representing a constant perceptual colour difference, at a constant luminance, at various positions, and in various directions, in the x, y diagram; it is clear that these distances vary greatly in length. The situation is rather like a flat map of the world, in which a constant real distance on the earth's surface is represented by different lengths on the map, at various positions and in various directions. As in the case of the map of the world, so in the map of colours in the chromaticity diagram, there is no complete solution to the problem so long as a flat surface is used; but, as in geography, so in colorimetry, some representations do introduce less distortion than others.

In Fig. 10 is shown a chromaticity diagram in which are plotted:

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3}$$

$$v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3}$$

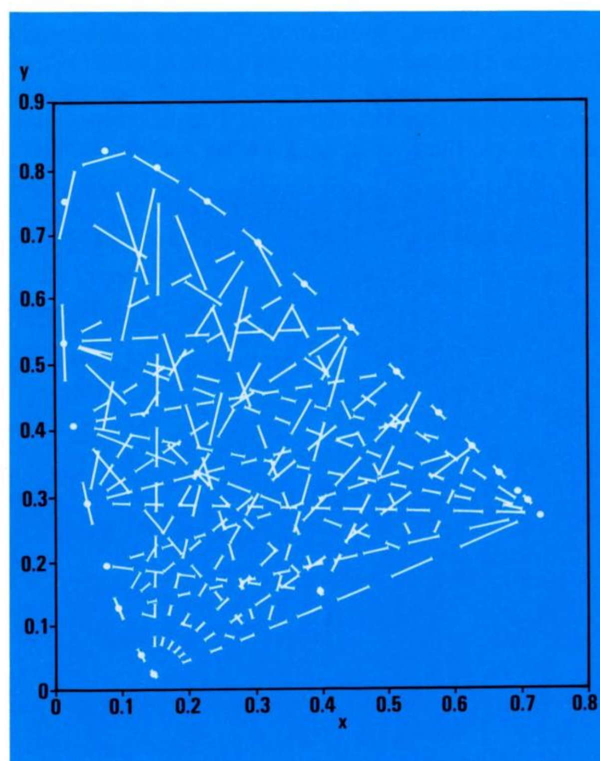


Fig. 9. Equally noticeable colour differences (at constant luminance) in the x, y diagram.

and, again, the short lines show distances representing a constant perceptual colour difference (at constant luminance). It is clear that, although there are still variations in the lengths of the lines, they are much more similar in length than in Fig. 9. The chromaticity diagram shown in Fig. 10 is known as the *CIE 1976 uniform-chromaticity scale diagram*, or the *CIE 1976 UCS diagram*, often referred to as the u′, v′ diagram. (In 1960 the CIE introduced a similar diagram in which u and v were plotted, where $u = u'$ and $v = 2/3\ v'$; this u, v diagram has now been superceded by the u′, v′ diagram). The u′, v′ diagram is very useful for representing the additive mixtures of the light emitted by phosphor primaries in television display devices.

Colour Difference Formulae

Uniform chromaticity diagrams, like all other chromaticity diagrams, only represent *proportions* of tristimulus values, not their actual values. They therefore only represent uniformly the magnitudes of colour differences for stimuli all having the same luminance. But, in general, when two colours are different from one another, they will not necessarily have the same luminance. Colour differences therefore have to be evaluated in a three-dimensional colour space, rather than on a two-dimensional chromaticity diagram. The CIE has developed two such spaces, the *CIE 1976 (L* u* v*) colour space* or

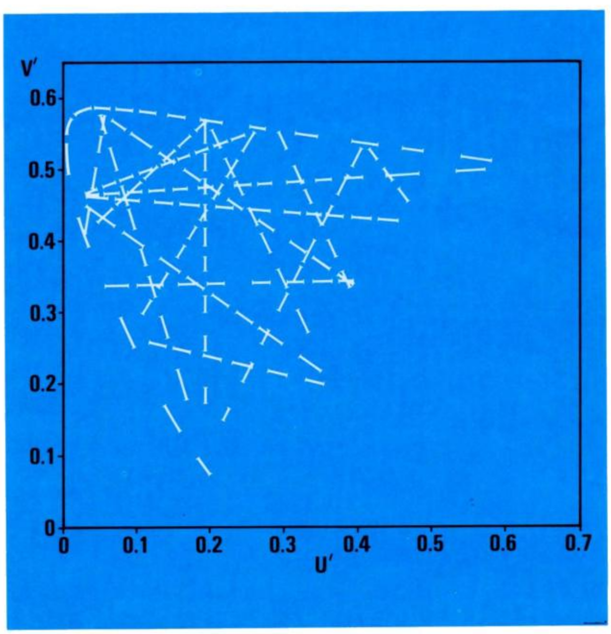


Fig. 10. The colour differences of Fig. 9 in the u′, v′ diagram.

CIELUV colour space, and the *CIE 1976 (L* a* b*) colour space* or *CIELAB colour space*. The CIELUV space is more directly applicable to television since it incorporates the u′, v′ chromaticity diagram, already described. It is illustrated in Fig. 11.

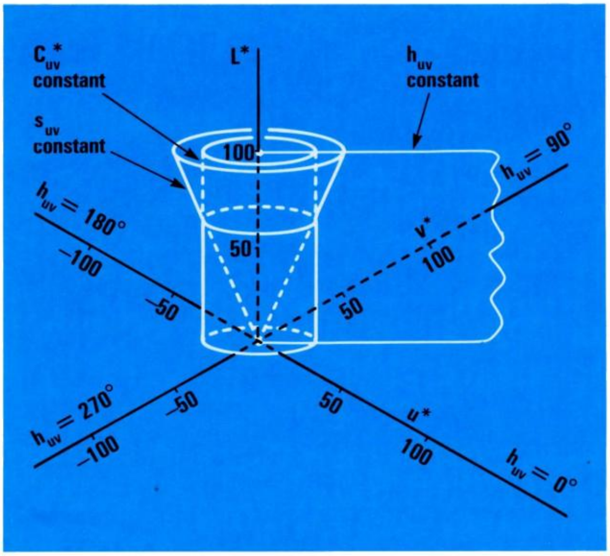


Fig. 11. The CIELUV colour space.

The CIELUV space is produced by plotting, along rectangular co-ordinates, the quantities L*, u*, v*, defined as follows:

$$L^* = 116(Y/Y_n)^{1/3} - 16$$
$$u^* = 13L^*(u' - u_n')$$
$$v^* = 13L^*(v' - v_n')$$

where Y, u′, v′, refer to the colour considered, and Y_n, u_n', v_n', refer to a suitably chosen reference white (if Y/Y_n is less then 0.008856, then L* is evaluated as $903.3Y/Y_n$, instead of by the formula for L* given above). The total difference between two colours, whose differences in L*, u* and v* are ΔL^*, Δu^*, and Δv^* respectively, is then evaluated as:

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{\frac{1}{2}}$$

In this L*, u*, v* system, approximate correlates of perceptually important colour attributes, as shown in Fig. 11, may be calculated as follows:

CIE 1976 lightness

$$L^* = 116(Y/Y_n)^{1/3} - 16,\ Y/Y_n > 0.008856$$

CIE 1976 u, v saturation

$$s_{uv} = 13\,[(u' - u'_n)^2 + (v' - v'_n)^2]^{\frac{1}{2}}$$

CIE 1976 u, v chroma

$$C^*_{uv} = (u^{*2} + v^{*2})^{\frac{1}{2}} = L^* s_{uv}$$

CIE 1976 u, v hue-angle

$$h_{uv} = \arctan\,[(v' - v'_n)/(u' - u'_n)] = \arctan\,(v^*/u^*)$$

CIE 1976 u, v hue-difference

$$\Delta H^*_{uv} = [(\Delta E^*_{uv})^2 - (\Delta L^*)^2 - (\Delta C^*_{uv})^2]^{\frac{1}{2}}$$

h_{uv} lies between 0° and 90° if v^* and u^* are both positive, between 90° and 180° if v^* is positive and u^* is negative, between 180° and 270° if v^* and u^* are both negative, and between 270° and 360° if v^* is negative and u^* is positive. CIE 1976 u, v hue-difference is introduced so that a colour difference ΔE^* can be broken up into components ΔL^*, ΔC^*, and ΔH^* whose squares sum to the square of ΔE^*. ΔH^*_{uv} is to be regarded as positive if indicating an increase in h_{uv} and negative if indicating a decrease in h_{uv}.

The advantage of these correlates over those mentioned earlier, dominant wavelength, excitation purity, and luminance factor, is that they offer scales that are much more perceptually uniform. Thus, with dominant wavelength, large changes in the value at the ends of the spectrum represent quite small changes in hue, whereas small changes in the middle of the spectrum represent large changes in hue; but h_{uv} being based on angles in the u′, v′ diagram, correlates much more uniformly with changes in hue. Similarly, excitation purity, being based on the x, y diagram, is less perceptually uniform as a correlate of saturation than is the case for s_{uv}, which is based on the u′, v′ diagram. With luminance factor, a given change for light colours, such as light greys, is much less noticeable than the same change for dark colours, such as dark greys; but the L^* function has been specially designed so that a given change in L^* represents a similar change in lightness for all reflecting colours from the lightest (such as whites and yellows) to the darkest (such as blacks and deep blues). CIE 1976 u, v chroma, C^*_{uv}, has been designed to correlate with perceived chroma; this is the perceptual attribute defined as colourfulness judged as a proportion of a similarly illuminated area that appears white or highly transmitting. It is equal to the product $s_{uv} \cdot L^*$, and the multiplication of the correlate of saturation, s_{uv}, by L^* allows for the fact that, for a given difference in the chromaticity of a colour from that of the reference white, its colourfulness decreases as the luminance factor is reduced; but by being based on relative tristimulus values (X, Y, Z) and not on absolute tristimulus values (X_a, Y_a, Z_a), this measure C^*_{uv} does not change as the level of illuminance is changed. Thus, an orange and a brown may have the same chromaticities, and therefore the same values of s_{uv}, and the same saturation. But the lower value of L^* for the brown will result in it having a lower C^*_{uv}, and it appears of lower chroma. But, if the illuminance level is changed, the values of C^*_{uv} will not change, and this represents the fact that the perceived chromas of the orange and brown remain fairly constant over a wide range of illuminances. At lower illuminances both the orange and the brown will look less colourful than at higher illuminances; they will also look less bright at the lower illuminances. Under specified viewing conditions, luminance can usually provide an approximate correlate with brightness, but does not provide a perceptually uniform scale; but there is at present no agreed measure that provides a correlate for colourfulness.

The CIELAB system, which was designed to be similar to certain systems used widely in the colourant industries, is similar to the CIELUV system, but has no associated chromaticity diagram and no correlate of saturation. The CIELAB space is produced by plotting along rectangular co-ordinates, the quantities L^*, a^*, b^*, defined as follows:

$$L^* = 116(Y/Y_n)^{1/3} - 16 \qquad Y/Y_n > 0.008856$$

$$a^* = 500\,[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}] \qquad X/X_n > 0.008856 \quad Y/Y_n > 0.008856$$

$$b^* = 200\,[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}] \qquad Z/Z_n > 0.008856$$

where X, Y, Z refer to the colour considered and X_n, Y_n, Z_n refer to a suitably chosen reference white. Colour differences in this system are evaluated as:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{\frac{1}{2}}$$

Approximate correlates of lightness, chroma, and hue in this system are calculated as follows:

CIE 1976 lightness

$$L^* = 116(Y/Y_n)^{1/3} - 16 \qquad Y/Y_n > 0.008856$$

CIE 1976 a, b chroma

$$C^*_{ab} = (a^{*2} + b^{*2})^{\frac{1}{2}}$$

CIE 1976 a, b hue-angle

$$h_{ab} = \arctan (b^*/a^*)$$

CIE 1976 a, b hue-difference

$$\Delta H^*_{ab} = [(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2]^{\frac{1}{2}}$$

These spaces are intended to apply to comparisons of differences between reflecting object colours of the same size and shape, viewed in identical white to middle-grey surroundings, by an observer photopically adapted to a field of chromaticity not too different from that of average daylight. They are not necessarily directly applicable to self-luminous colours such as are used in typical television displays.

This concludes a brief summary of the main colorimetric recommendations of the CIE. The remainder of this review is concerned with the application of colorimetry to television broadcasting.

APPENDIX

The CIE colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$.

λ(nm)	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
380	0.0014	0.0000	0.0065
385	0.0022	0.0001	0.0105
390	0.0042	0.0001	0.0201
395	0.0076	0.0002	0.0362
400	0.0143	0.0004	0.0679
405	0.0232	0.0006	0.1102
410	0.0435	0.0012	0.2074
415	0.0776	0.0022	0.3713
420	0.1344	0.0040	0.6456
425	0.2148	0.0073	1.0391
430	0.2839	0.0116	1.3856
435	0.3285	0.0168	1.6230
440	0.3483	0.0230	1.7471
445	0.3481	0.0298	1.7826
450	0.3362	0.0380	1.7721
455	0.3187	0.0480	1.7441
460	0.2908	0.0600	1.6692
465	0.2511	0.0739	1.5281
470	0.1954	0.0910	1.2876
475	0.1421	0.1126	1.0419
480	0.0956	0.1390	0.8130
485	0.0580	0.1693	0.6162
490	0.0320	0.2080	0.4652
495	0.0147	0.2586	0.3533
500	0.0049	0.3230	0.2720
505	0.0024	0.4073	0.2123
510	0.0093	0.5030	0.1582
515	0.0291	0.6082	0.1117
520	0.0633	0.7100	0.0782
525	0.1096	0.7932	0.0573
530	0.1655	0.8620	0.0422
535	0.2257	0.9149	0.0298
540	0.2904	0.9540	0.0203
545	0.3597	0.9803	0.0134
550	0.4334	0.9950	0.0087
555	0.5121	1.0000	0.0057
560	0.5945	0.9950	0.0039
565	0.6784	0.9786	0.0027
570	0.7621	0.9520	0.0021
575	0.8425	0.9154	0.0018
580	0.9163	0.8700	0.0017
585	0.9786	0.8163	0.0014
590	1.0263	0.7570	0.0011
595	1.0567	0.6949	0.0010
600	1.0622	0.6310	0.0008
605	1.0456	0.5668	0.0006
610	1.0026	0.5030	0.0003
615	0.9384	0.4412	0.0002
620	0.8544	0.3810	0.0002
625	0.7514	0.3210	0.0001
630	0.6424	0.2650	0.0000
635	0.5419	0.2170	0.0000
640	0.4479	0.1750	0.0000
645	0.3608	0.1382	0.0000
650	0.2835	0.1070	0.0000
655	0.2187	0.0816	0.0000
660	0.1649	0.0610	0.0000
665	0.1212	0.0446	0.0000
670	0.0874	0.0320	0.0000
675	0.0636	0.0232	0.0000
680	0.0468	0.0170	0.0000
685	0.0329	0.0119	0.0000
690	0.0227	0.0082	0.0000
695	0.0158	0.0057	0.0000
700	0.0114	0.0041	0.0000
705	0.0081	0.0029	0.0000
710	0.0058	0.0021	0.0000
715	0.0041	0.0015	0.0000
720	0.0029	0.0010	0.0000
725	0.0020	0.0007	0.0000
730	0.0014	0.0005	0.0000
735	0.0010	0.0004	0.0000
740	0.0007	0.0002	0.0000
745	0.0005	0.0002	0.0000
750	0.0003	0.0001	0.0000
755	0.0002	0.0001	0.0000
760	0.0002	0.0001	0.0000
765	0.0001	0.0000	0.0000
770	0.0001	0.0000	0.0000
775	0.0001	0.0000	0.0000
780	0.0000	0.0000	0.0000

PHILIP DARBY, MBE,
C.Eng., MIERE.
A biographical note appears
on page 4.

Colorimetry in Television

by P. J. Darby

Synopsis

The first essential in the specification of a colour television system is to determine the chromaticity co-ordinates of the receiver display tube, together with the white point. Transformation equations can then be derived to establish the required spectral sensitivities of the camera channels.

Colorimetric principles may be applied to the encoded colour signals, using the concept of transmission primaries. A hypothetical linear system is considered first, to illustrate the fundamental relationships.

Since the display tube has a non-linear transfer characteristic the studio output signals must be gamma-corrected. However, the overall system requires a transfer characteristic, somewhat greater than unity, to compensate for average viewing conditions, and this non-linearity introduces changes in chromaticity and luminance.

Consideration is given to the concept of constant luminance and the reproduction of colour television transmissions on black and white receivers.

Image Reproduction

The principles of additive colour matching, which form the basis of colorimetry, are applied by all colour television systems in the process of image reproduction. However, the primary stimuli used by the CIE to define the standard observer are pure spectral radiations of low luminous efficacy. Different primaries must be employed in television systems, to achieve adequate luminance levels from the display.

It is somewhat paradoxical that the first essential in the detailed specification of a colour television system is to determine the chromaticity co-ordinates of the display-tube phosphors, and the white point, to be used by the receiver at the end of the broadcasting chain. However, the design of colour cameras and telecine scanners must be optimised according to the display tube specification, to ensure that the system will reproduce the original colours.

When colour television was first introduced in the USA, the display tubes used the primary colours of the NTSC system, with Illuminant C as the reference white. However, shortly after the PAL system was established as the UK standard, the broadcasters and the equipment manufacturers agreed to introduce new display tube phosphors to achieve greater luminance and consistency of colour reproduction. They also agreed to adopt Illuminant D_{65} as the reference white, since this was a closer approach to natural daylight. It is rather unfortunate that the signal processing relationships used in coders and decoders are still based on the NTSC primaries and Illuminant C; however, expert opinion contends that the expense and inconvenience of changing to the correct relationships would not be worthwhile, since only the compatibility of black and white pictures would benefit.

The two sets of chromaticity co-ordinates are as follows:

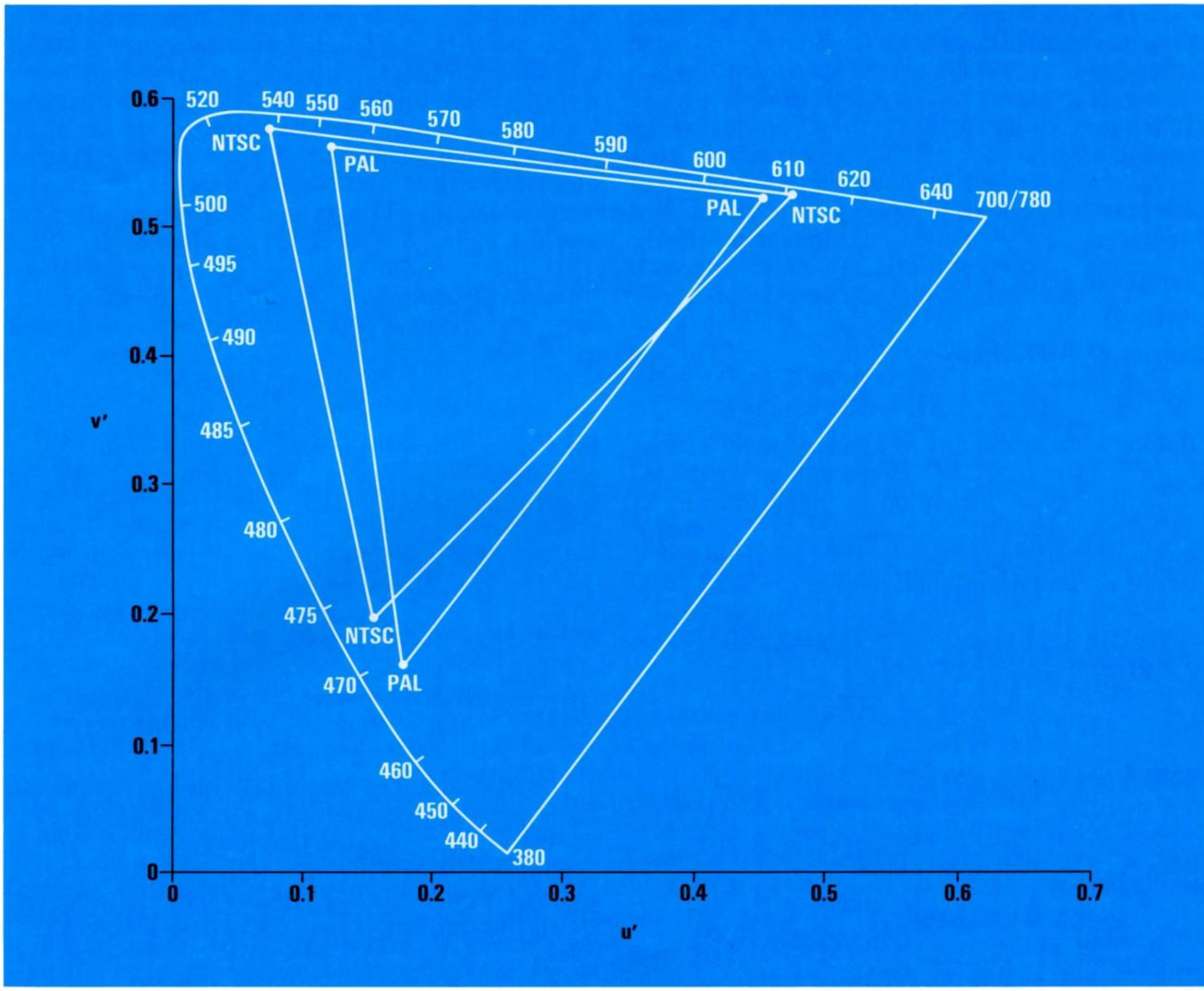


Fig. 1. NTSC and PAL television system primaries. (Wavelengths in nm.)

NTSC System

	x	*y*	*z*	*u'*	*v'*
Red primary	0.67	0.33	0.00	0.477	0.528
Green primary	0.21	0.71	0.08	0.076	0.576
Blue primary	0.14	0.08	0.78	0.152	0.195
Illuminant C	0.3101	0.3162	0.3737	0.2009	0.4610

UK PAL SYSTEM

(Also the EBU Standard)

	x	*y*	*z*	*u'*	*v'*
Red primary	0.64	0.33	0.03	0.451	0.523
Green primary	0.29	0.60	0.11	0.121	0.561
Blue primary	0.15	0.06	0.79	0.175	0.157
Illuminant D_{65}	0.3127	0.3290	0.3583	0.1978	0.4683

These two sets of co-ordinates are illustrated on the u′, v′ diagram of Fig. 1.

In both of these systems, the units used for expressing the amounts of the red, green, and blue primary colours are such that equal amounts are required to match the illuminant adopted. We now need to evaluate the relative luminous fluxes, or relative luminances as they are usually called, of these units. Taking the NTSC system first, we proceed as follows.

For the production of a colour that matches Illuminant S_c, let the relative luminances of the NTSC red, green and blue units be l, m and n, respectively, with $l + m + n = 1$. We can now list the following tristimulus values:

	X	Y	Z
0.33 lumens of NTSC Red	0.67	0.33	0.00
0.71 lumens of NTSC Green	0.21	0.71	0.08
0.08 lumens of NTSC Blue	0.14	0.08	0.78
0.3162 lumens of S_c	0.3101	0.3162	0.3737
1 lumen of S_c	0.3101/0.3162	1	0.3737/0.3162
l lumens of NTSC Red	$\frac{l}{0.33}0.67$	$\frac{l}{0.33}0.33$	$\frac{l}{0.33}0.00$
m lumens of NTSC Green	$\frac{m}{0.71}0.21$	$\frac{m}{0.71}0.71$	$\frac{m}{0.71}0.08$
n lumens of NTSC Blue	$\frac{n}{0.08}0.14$	$\frac{n}{0.08}0.08$	$\frac{n}{0.08}0.78$

But the additive mixture of l lumens of NTSC Red with m lumens of NTSC Green and n lumens of NTSC Blue is by definition a colour match to $l+m+n=1$ lumen of S_c; hence the X, Y, and Z tristimulus values must be the same as those for 1 lumen of S_c. This means that:

$$(0.67/0.33)\,l + (0.21/0.71)m + (0.14/0.08)n = 0.3101/0.3162$$

$$l + m + n = 1$$

$$(0.00/0.33)l + (0.08/0.71)m + (0.78/0.08)n = 0.3737/0.3162$$

Solving for l, m, and n, we obtain:

$$l=0.299 \qquad m=0.587 \qquad n=0.114$$

These values enable the following transformation equations to be obtained, linking R, G, and B, the tristimulus values in the NTSC RGB system (measured in the special units, l, m, and n, respectively), with the X, Y, Z tristimulus values:

$$X=0.607R+0.174G+0.200B$$
$$Y=0.299R+0.587G+0.114B$$
$$Z=0.000R+0.066G+1.116B$$

The reverse transformation equations, obtained by solving for R, G, and B, are also useful:

$$R=\ \ 1.909X-0.532Y-0.288Z$$
$$G=-0.985X+1.997Y-0.028Z$$
$$B=\ \ 0.058X-0.119Y+0.902Z$$

A similar set of calculations can be carried out for the PAL system primaries, normalized to Illuminant D_{65}, and this yields the following sets of transformation equations:

$$X=\ \ 0.431R+0.342G+0.178B$$
$$Y=\ \ 0.222R+0.707G+0.071B$$
$$Z=\ \ 0.020R+0.130G+0.939B$$

$$R=\ \ 3.063X-1.393Y-0.476Z$$
$$G=-0.969X+1.876Y+0.042Z$$
$$B=\ \ 0.068X-0.229Y+1.069Z$$

The R, G and B co-efficients in the above equation for Y are the true relative luminances of the EBU phosphors. It can be seen that the green contribution is considerably greater than the traditional NTSC value of 59%, while the red and blue contributions are significantly lower than the corresponding NTSC values.

It is important to remember that the values of R, G and B represent amounts of the primaries. Each value is proportional to the light output of the primary and this bears a non-linear relationship to the tube driving voltage. This relationship is a power function and typical display tubes produce a light output proportional to the driving voltage raised to the power 2.8 ± 0.3. This exponent is known as the 'gamma factor' or 'transfer characteristic'.

Ignoring the possible effects of stray light reflected from the screen, the image luminance will conform to the following relationship:-

$$L = k(0.222E_R^{\gamma} + 0.707E_G^{\gamma} + 0.071E_B^{\gamma})\ \mathrm{cd/m^2}$$

where k is a constant,
E_R, E_G & E_B are the tube drive voltages and
γ is the gamma factor

A control room monitor adjusted to comply with CCIR Recommendation 500 has a white level luminance of 70cd/m² and amplifier gains are normally set so that the Red, Green and Blue channel input voltages required to match Illuminant D_{65} are each 700mV. Since this represents the maximum drive level to each channel, it is convenient to normalise each input in relation to the same value. Under these circumstances, $E_R = E_G = E_B = 1.0$ and $k = 70$.

If $\gamma = 2.8$, it is instructive to consider the effect of halving the drive voltage to each channel:

$$L = 70(0.5)^{2.8} = 10.05 \text{ cd/m}^2$$

Although this is a seven-fold reduction in luminance and represents a considerable departure from linearity, the chromaticity remains at Illuminant D_{65}, because the voltages are still equal. However, with unequal signals, a change in chromaticity would be involved and this will be considered later.

To maintain a linear relationship over the whole transmission chain it is necessary to apply gamma correction to the television camera output. Since the plumbicon camera tube has a nearly linear transfer characteristic, full correction would require an exponent of $1/2.8 = 0.357$, but the value normally used is about 0.45, giving an overall system gamma of approximately 1.26. It has been established that an overall gamma of unity results in a colour television display which is lacking in contrast and saturation, because under average viewing conditions the 'contrast' perceived by the viewer is reduced by several effects. These include the small size of the screen, and the fact that the level of light coming from the image is usually much lower than that of the original scene. The level of background lighting in which the screen is viewed also affects the contrast and saturation perceived by the viewer. It is found that the overall raising of the system gamma to a value between 1.2 and 1.3 results in more satisfactory image reproduction of typical scenes for the average viewer.

Origination of the Colour Signal

In the previous section expressions were derived for the tristimulus values, X, Y and Z of colours displayed on picture tubes, in terms of the R, G and B components, for the standards of the NTSC and PAL colour systems. It might be assumed that an ideal television system would reproduce at the receiver the identical luminance and chromaticity of each corresponding element in the original scene. The colour camera analyses the total light from the scene, element by element, and produces three separate signals appropriate to drive the red, green and blue guns in the display tubes. Although it has been established that, for good reasons, the overall system does not maintain perfect linearity, it is convenient, initially, to analyse the system as it would be if it were linear. Considering first the NTSC system, the reverse transformation equations already derived:

$$\begin{aligned} R &= 1.909X - 0.532Y - 0.288Z \\ G &= -0.985X + 1.997Y - 0.028Z \\ B &= 0.058X - 0.119Y + 0.902Z \end{aligned}$$

tell us how much of the red, green, and blue light (measured in the special units, *l*, m, and n, respectively) is needed to match any colour whose CIE tristimulus values are X, Y, and Z. Hence if the camera had spectral sensitivities $R(\lambda)$, $G(\lambda)$, $B(\lambda)$:

$$\begin{aligned} R(\lambda) &= 1.909\bar{x}(\lambda) - 0.532\bar{y}(\lambda) - 0.288\bar{z}(\lambda) \\ G(\lambda) &= -0.985\bar{x}(\lambda) + 1.997\bar{y}(\lambda) - 0.028\bar{z}(\lambda) \\ B(\lambda) &= 0.058\bar{x}(\lambda) - 0.119\bar{y}(\lambda) + 0.902\bar{z}(\lambda) \end{aligned}$$

they would produce signals E_R, E_G, E_B, that would (in a linear system) generate colours having the correct XYZ tristimulus values. Such a set of spectral sensitivity curves is shown in Fig. 2. As is to be expected, these curves have negative portions, because some colours cannot be matched directly with any mixture of the three primaries.

If it was possible to use a camera analysis that

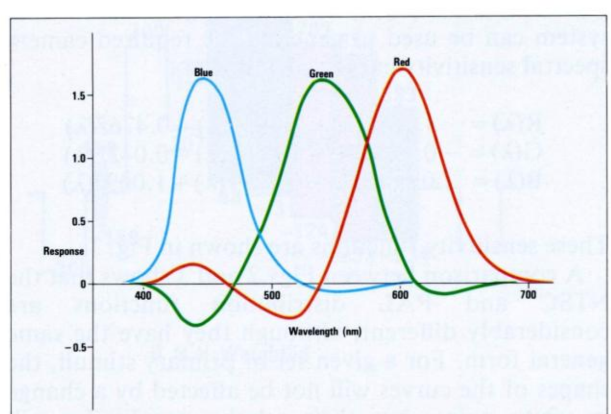


Fig. 2. Distribution functions for the NTSC primaries balanced to match Illuminant C.

conformed with these distribution functions at all wavelengths, its output signals could be used in an attempt to reproduce the original colours of the scene by driving the display tube both positively and negatively to seek a colorimetric match. However, since negative light cannot be produced, such an attempt would fail. The range of reproducible colours is restricted to those falling within the triangle defined by the NTSC primaries as shown in Fig. 1. Nevertheless, this shortcoming should be recognised as a limitation of the display system. The camera analysis should still match the spectral distributions of Fig. 2 as closely as possible in order to maintain the correct hue and saturation.

In practical colour television cameras, the light from the main lens is split into three bands. Dichroic mirrors and shaping filters are used to obtain responses for the red, green and blue channels that match as closely as possible the major positive lobes of the distribution functions. The electrical signals from the three channels thus correspond to the positive areas of the distribution functions and it is possible, by careful calculation, to devise a matrix which will combine proportions of the three signals, with appropriate polarity at each wavelength, to introduce negative lobes.

Such a matrix cannot be totally effective unless the spectral location of each positive maximum corresponds to a point where a negative peak output is required from another channel. Although such an ideal situation does not normally exist in practice, it is possible, by the use of matrices, to achieve a very considerable improvement in the colour reproduction of the system.

Considering now the PAL system, with Illuminant D_{65} as the white point, the inverse equations for that system can be used to generate the required camera spectral sensitivity curves, as follows:

$$R(\lambda) = 3.063\bar{x}(\lambda) - 1.393\bar{y}(\lambda) - 0.476\bar{z}(\lambda)$$
$$G(\lambda) = -0.969\bar{x}(\lambda) + 1.876\bar{y}(\lambda) + 0.042\bar{z}(\lambda)$$
$$B(\lambda) = 0.068\bar{x}(\lambda) - 0.229\bar{y}(\lambda) + 1.069\bar{z}(\lambda)$$

These sensitivity functions are shown in Fig. 3.

A comparison between Figs.2 and 3 shows that the NTSC and PAL distribution functions are considerably different, although they have the same general form. For a given set of primary stimuli, the shapes of the curves will not be affected by a change in white point, but their relative amplitudes will change. However, in this case, the primary chromaticities and the white point are different and,

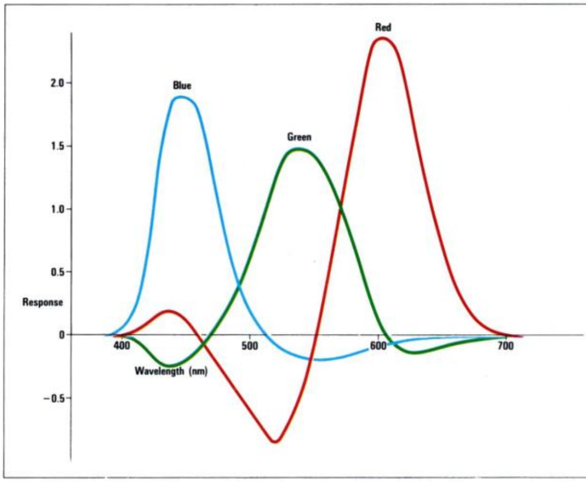


Fig. 3. Distribution functions for the PAL primaries balanced to match Illuminant D_{65}.

accordingly, the curves show some changes in shape as well as relative amplitude. Although the wavelengths of the negative peaks of these curves are not all coincident with those of positive peaks, it is possible to construct a matrix that will provide a reasonably close approximation to the required analysis.

Signal Transmission

So far, consideration has been given to the production of three separate signals, representing the red, green and blue amounts of light from the studio scene, and to a means by which these three signals can be used to produce a colour picture. However, it is essential that these three colour signals, known as the colour separation signals, should be encoded and transmitted in such a manner that a black and white receiver will obtain a virtually normal luminance signal and that a colour receiver can display satisfactory black and white pictures when necessary. These requirements are called, respectively, 'compatibility' and 'reverse compatibility'.

The studio camera is lined-up using a white test surface, so that the red, green and blue output voltages, after gamma correction, are all equal. If these signals are applied to a suitable matrix, a luminance signal can be obtained as follows:

$$E'_Y = 0.299\,E'_R + 0.587E'_G + 0.114E'_B$$

where the symbol E′ indicates a 'gamma-corrected' voltage, $E^{1/\gamma}$.

As explained in the introduction to this article, these relative luminances are strictly correct only for the NTSC display primaries, balanced to Illuminant C, but, for historical reasons they are still used in the PAL system.

The luminance signal may be transmitted for use in monochrome and colour receivers and it follows that only two additional colour signals are required, since the third can be obtained by computation in the receiver. It would be possible to transmit, say, red and green and to derive blue from the luminance signal. However, if this was done, a black and white transmitter, radiating only the luminance information, would produce a blue picture on a colour receiver. Such a system would have compatibility but would lack reverse compatibility.

A much more satisfactory system is to transmit two colour signals having amplitudes related to the degree of saturation, because, such signals fall to zero during black and white transmissions. This can be achieved by using two of the colour difference signals, $(E'_R - E'_Y)$, $(E'_G - E'_Y)$ and $(E'_B - E'_Y)$. Since green makes the largest contribution to luminance, $(E'_G - E'_Y)$ normally has a relatively low value and this signal would be most affected by noise. Consequently the colour-difference signals used in PAL are $(E'_B - E'_Y)$ and $(E'_R - E'_Y)$.

If the full amplitude colour-difference signals were used to modulate the chrominance subcarrier, the voltage excursions of the composite colour signal would be excessive at both the positive and negative extremes. Large positive excursions of the video signal would require a corresponding increase in the transmitter carrier amplitude at white level, thus reducing the available modulation range. Excessive negative excursions of the video signal could cause gross interference with the synchronising signals and would also involve a reduction in the modulation range. Furthermore, the specification of the vision links would need to be augmented to handle larger video amplitudes.

It was decided to restrict the chrominance signal excursions to peak levels of $33\frac{1}{3}\%$ above and below the full range of the luminance signal (i.e. blanking level to white level). Both the $(E'_B - E'_Y)$ and $(E'_R - E'_Y)$ signals must be reduced to yield appropriate levels for the chrominance modulating signals, E'_U and E'_V. To derive the values of the appropriate weighting factors it is necessary to consider that both yellow and cyan signals require reduction of their positive excursions, but by different amounts, while red and blue signals require reduction of their negative excursions, also by different amounts. Because the luminance and

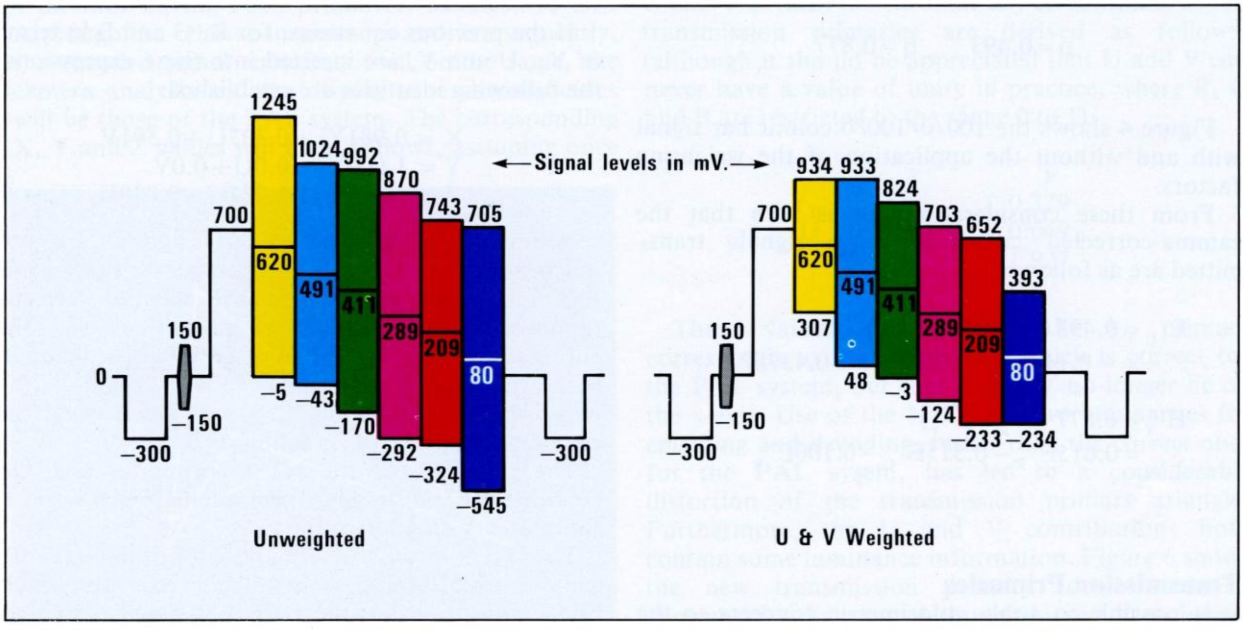


Fig. 4. 100/0/100/0 colour bar signal with and without U and V weighting (coloured areas represent different phases of chrominance subcarrier).

chrominance amplitudes of these two pairs of colours are symmetrically disposed in relation to white level and blanking level, the same weighting factors will yield the same reduction at both extremes.

The two factors that will meet these requirements may be derived as follows:

Positive voltage limit
$= 1.33333$
$= E'_L + [(E'_B - E'_Y)^2 p^2 + (E'_R - E'_Y)^2 q^2]^{\frac{1}{2}}$

Where p = U signal weighting factor
and q = V signal weighting factor

Substituting the values corresponding to full-amplitude, fully-saturated yellow and cyan signals gives the following simultaneous equations.

For Yellow
$$1.33333 = 0.88552 + (0.88552^2 p^2 + 0.11448^2 q^2)^{\frac{1}{2}}$$

For Cyan
$$1.33333 = 0.70108 + (0.29892^2 p^2 + 0.70108^2 q^2)^{\frac{1}{2}}$$

The solutions to these equations are:

$$p = 0.493 \qquad q = 0.877$$

Figure 4 shows the 100/0/100/0 colour bar signal with and without the application of the weighting factors.

From these considerations, it is seen that the gamma-corrected colour-difference signals transmitted are as follows:

$$\begin{aligned} E'_U &= 0.493\,(E'_B - E'_Y) \\ &= -0.147E'_R - 0.289E'_G + 0.437E'_B \end{aligned}$$

$$\begin{aligned} E'_V &= 0.877\,(E'_R - E'_Y) \\ &= 0.615E'_R - 0.515E'_G - 0.100E'_B \end{aligned}$$

Transmission Primaries

It is possible to apply colorimetric concepts to the encoded signal, in terms of 'transmission primaries', having the following relationships:

$$\begin{aligned} Y_T &= 0.299R + 0.587G + 0.114B \\ U &= -0.147R - 0.289G + 0.437B \\ V &= -0.615R \quad 0.515G - 0.100B \end{aligned}$$

Where Y_T = The luminance signal,
U and V = The colour difference signals
R, G and B = The colour separation signals in a hypothetical linear system, based on NTSC primary chromaticities.

The inverse form of these equations yields the following expressions which correspond to the outputs of a decoder:

$$\begin{aligned} R &= 1Y_T + 0\,U + 1.140V \\ G &= 1Y_T - 0.394U - 0.581V \\ B &= 1Y_T + 2.028U + 0\,V \end{aligned}$$

At this point, it is instructive to consider the effect of applying these signals to a hypothetical monitor having NTSC primaries and a linear transfer characteristic.

X, Y and Z tristimulus values corresponding to the NTSC primaries are given by the following equations, derived above.

$$\begin{aligned} X &= 0.607R + 0.174G + 0.200B \\ Y &= 0.299R + 0.587G + 0.114B \\ Z &= 0.0R + 0.066G + 1.116B \end{aligned}$$

If the previous equations, for R, G and B in terms of Y_T, U and V, are inserted into these expressions, the following identities are established:

$$\begin{aligned} X &= 0.981Y_T + 0.337U + 0.591V \\ Y &= 1.000Y_T + 0.0U + 0.0V \\ Z &= 1.182Y_T + 2.237U - 0.038V \end{aligned}$$

Although, in practice, Y_T, U and V are not independent variables, it is legitimate to ignore this fact in order to establish the location of the (hypothetical) transmission primaries on the chromaticity chart. If values of 1, 0, 0; 0, 1, 0 and 0, 0, 1 are assigned respectively to Y_T, U and V, the corresponding values of X, Y and Z will yield the required co-ordinates, as follows:

The positions of the NTSC primaries and the hypothetical transmission primaries are shown in a chromaticity diagram in Fig. 5.

The Y_T co-ordinates are those of Illuminant C, while those of U and V lie on the x-axis, for which $y = 0$, indicating that the U and V signals carry no luminance information, but only colour information. It is also evident that U and V lie on the x-axis at

TABLE 1

TRANSMISSION PRIMARIES			TRISTIMULUS VALUES			CHROM. CO-ORDINATES	
Y_T	U	V	X	Y	Z	x	y
1	0	0	0.981	1.000	1.182	0.310	0.316
0	1	0	0.337	0.0	2.237	0.131	0
0	0	1	0.591	0.0	−0.038	1.069	0

points intersected by extensions of the Green-Blue and Green-Red connecting lines respectively. This is to be expected, since the Green-Blue line represents all colours with no red content and the Green-Red line represents all colours with no blue content. The transmission system may thus be represented by a colour triangle connecting the primaries. However, it must be remembered that Y_T has luminance only, with no colour, while both U and V can be negative or positive but that U is restricted to the amplitude range ± 0.437 and V is restricted to the amplitude range ± 0.615. Since U and V can have negative values, colours outside the Y_TUV triangle can be transmitted.

In practice, a PAL decoder will be associated with a monitor having PAL primaries, balanced to D_{65}. Although the relative luminances and, consequently, the encoded signal equations, will be the same, the camera analysis and the display tube chromaticities will be those of the PAL system. The corresponding X, Y and Z values will be as follows, assuming once again a monitor with a linear transfer characteristic:

$$X = 0.431R + 0.342G + 0.178B$$
$$Y = 0.222R + 0.707G + 0.071B$$
$$Z = 0.020R + 0.130G + 0.939B$$

If the equations for R, G and B in terms of Y_T, U and V are substituted in these expressions, the following identities may be established:

$$X = 0.951Y_T + 0.226U + 0.293V$$
$$Y = 1.0Y_T - 0.135U - 0.158V$$
$$Z = 1.089Y_T + 1.853U - 0.053V$$

Assigning values of 1, 0, 0; 0, 1, 0 and 0, 0, 1 to Y_T, U and V in turn, the chromaticity co-ordinates of the transmission primaries are derived as follows, (although it should be appreciated that U and V can never have a value of unity in practice, where R, G and B are restricted to the range 0 to 1):

	x	*y*
Y_T	0.313	0.329
U	0.116	−0.069
V	3.573	−1.927

These values indicate that the Y_T primary corresponds to Illuminant D_{65}, which is correct for the PAL system, but that U and V no longer lie on the x-axis. Use of the NTSC relative luminances for encoding and decoding, rather than the correct ones for the PAL sysem, has led to a considerable distortion of the transmission primary triangle. Furthermore, the U and V contributions both contain some luminance information. Figure 6 shows the new transmission primary locations on a chromaticity diagram. Although U and V no longer lie on the x-axis, they are still located on extensions of the Green-Blue and Green-Red connecting lines.

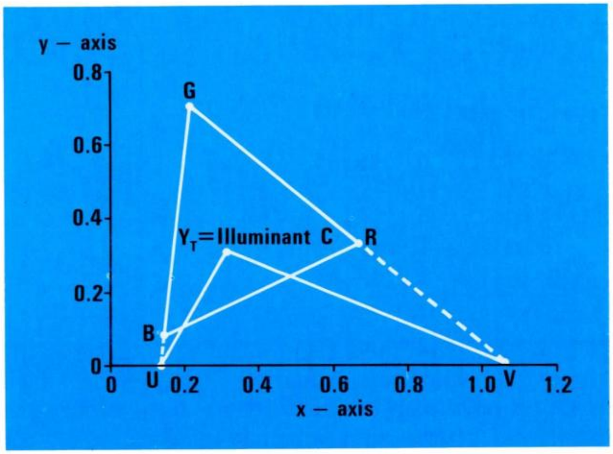


Fig. 5. Locations of hypothetical transmission primaries on an x, y chromaticity diagram.

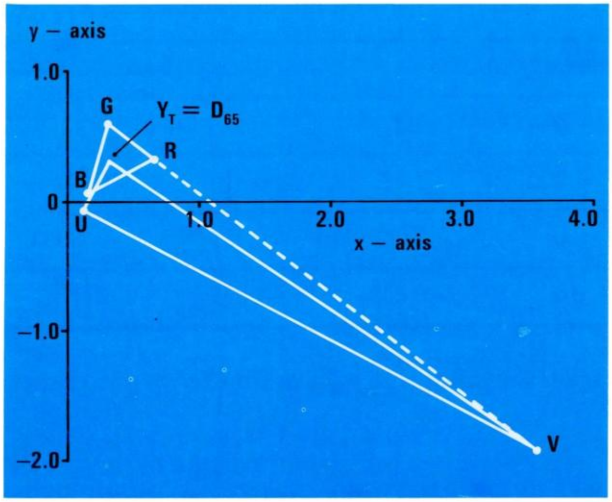


Fig. 6. Locations of transmission primaries for a linear PAL system

Of course, in this case the RGB primaries are those of the PAL system instead of those of the NTSC system shown in Fig. 5.

The Effects of Non-Linearity

The relationships illustrated in Figs.5 and 6 apply to linear systems and, consequently, they are not fully descriptive of practical television transmission systems.

As discussed earlier, the light emitted by each of the three display tube primary sources is proportional to the corresponding drive voltage raised to a certain power, known as the gamma factor. This factor varies with different display tubes and with different driving conditions. Furthermore, the effective gamma factor is not constant throughout the grey scale since it depends on the alignment of the displayed levels corresponding to 'black' and 'white', on the ambient lighting and on the surrounding areas in the observer's field of view. For purposes of calculation, it is a reasonable approximation to assume that the display tube gamma factor is about 2.8 ($\gamma = 2.8$).

It has been established previously that the red, green and blue colour separation signals from a picture source, such as a camera, are 'gamma-corrected' to compensate for the display tube characteristic but that the overall system gamma is about 1.26 rather than unity.

The normal correction exponent is 0.45 and the relationship between the transmission primaries and the original colour separation signals is given by the following equations:

$$
\begin{aligned}
E_R{}^{0.45} &= 1.0Y_T + 0.0U + 1.14V \\
E_G{}^{0.45} &= 1.0Y_T - 0.394U - 0.581V \\
E_B{}^{0.45} &= 1.0Y_T + 2.028U + 0.0V
\end{aligned}
$$

The tristimulus values of the reproduced colours will be proportional to values given by the following expressions, which take account of the combined exponents of the transmission system and the display tube ($0.45 \times 2.8 = 1.26$):

$$
\begin{aligned}
X &= 0.431E_R{}^{1.26} + 0.342E_G{}^{1.26} + 0.178E_B{}^{1.26} \\
Y &= 0.222E_R{}^{1.26} + 0.707E_G{}^{1.26} + 0.071E_B{}^{1.26} \\
Z &= 0.020E_R{}^{1.26} + 0.130E_G{}^{1.26} + 0.939E_B{}^{1.26}
\end{aligned}
$$

For such a simple power-law relationship, a method of combining these two sets of equations may be based on an analysis given by Hacking in 1966[1] and further developed by Sproson in 1983[2].

In this case, advantage can be taken of the following relationships

$$
\begin{aligned}
E_R{}^{1.26} &= E_R{}^{0.81}E_R{}^{0.45} = K_R(1.0Y_T + 0.0U + 1.140V) \\
E_G{}^{1.26} &= E_G{}^{0.81}E_G{}^{0.45} = K_G(1.0Y_T - 0.394U - 0.581V) \\
E_B{}^{1.26} &= E_B{}^{0.81}E_B{}^{0.45} = K_B(1.0Y_T + 2.028U + 0.0V)
\end{aligned}
$$

where $K_R = E_R{}^{0.81}$, $K_G = E_G{}^{0.81}$ and $K_B = E_B{}^{0.81}$

These expressions may now be substituted in the equations for X, Y and Z as follows:

$$
\begin{aligned}
X = {} & (0.431K_R + 0.342K_G + 0.178K_B)Y_T \\
& - (0.135K_G - 0.361K_B)U \\
& + (0.491K_R - 0.199K_G)V
\end{aligned}
$$

$$
\begin{aligned}
Y = {} & (0.222K_R + 0.707K_G + 0.071K_B)Y_T \\
& - (0.279K_G - 0.144K_B)U \\
& + (0.253K_R - 0.411K_G)V
\end{aligned}
$$

$$
\begin{aligned}
Z = {} & (0.020K_R + 0.130K_G + 0.939K_B)Y_T \\
& - (0.051K_G - 1.904K_B)U \\
& + (0.023K_R - 0.076K_G)V
\end{aligned}
$$

It is clear from these relationships that none of the three transmission primaries occupies a fixed position on the chromaticity chart and we have the somewhat bizarre situation that the location of the transmission primaries depends upon the colour being transmitted.

However, if the scene is neutral (where $E_R = E_G = E_B$), the relationships will be the same as those of a corresponding system with a linear characteristic, because each coefficient will be similarly weighted

Because the overall system transfer characteristic is 1.26, rather than unity, the reproduced chromaticity will be determined not only by the true values of the original scene, as represented by the colour separation signals E_R, E_G and E_B, but it will also depend on the relative amplitudes of the three signals. For most colours, the reproduced hue and saturation will be somewhat different from the original, but there will be no change at the white point, nor for any full-amplitude colour where one or more of the primaries makes no contribution (ie Red, Green, Blue, Yellow, Cyan, Magenta). Fig. 7 illustrates these changes in chromaticity for a selection of colours on a u′, v′ diagram.

The chromaticities and relative luminances of the transmission primaries can be ascertained by successively substituting 1, 0, 0; 0, 1, 0 and 0, 0, 1 for Y_T, U and V, in the previous equations, with the following results:

luminance U and V signals under certain conditions. The following equations may be written:

If $0.144K_B = 0.279K_G$, U has zero luminance
If $0.411K_G = 0.253K_R$, V has zero luminance

Under these conditions

$$\frac{0.144^{1.26/0.81}}{0.279} = \frac{G}{B} \quad \text{and} \quad \frac{0.253^{1.26/0.81}}{0.411} = \frac{G}{R}$$

Where G/B and G/R are the ratios of two colours on the display which correspond to zero-luminance U and V signals respectively. This gives:

$$\frac{G}{B} = 0.357 \quad \text{and} \quad \frac{G}{R} = 0.470$$

These ratios correspond to a particular colour with the primaries in the proportions, red 2.128, green 1.0, blue 2.801 which, to use Sproson's terminology, could be described as the balance point of the PAL system, with an overall transfer characteristic of 1.26. The situation is illustrated graphically in Fig. 8.

TABLE 2

PRIMARY	CHROMATICITY	RELATIVE LUMINANCE
Y_T	$x = \dfrac{0.431K_R + 0.342K_G + 0.178K_B}{0.673K_R + 1.179K_G + 1.188K_B}$	$0.222K_R + 0.707K_G + 0.071K_B$
	$y = \dfrac{0.222K_R + 0.707K_G + 0.071K_B}{0.673K_R + 1.179K_G + 1.188K_B}$	
U	$x = \dfrac{-0.135K_G + 0.361K_B}{-0.465K_G + 2.409K_B}$	$-0.279K_G + 0.144K_B$
	$y = \dfrac{-0.279K_G + 0.144K_B}{-0.465K_G + 2.409K_B}$	
V	$x = \dfrac{0.491K_R - 0.199K_G}{0.767K_R - 0.686K_G}$	$0.253K_R - 0.411K_G$
	$y = \dfrac{0.253K_R - 0.411K_G}{0.767K_R - 0.686K_G}$	

As with the hypothetical linear version discussed earlier, the U and V signals carry luminance information. However, the application of non-linear characteristics has introduced the possibility of zero-

As stated previously some luminance information is carried by the colour-difference signals and this constitutes a departure from an ideal situation. Since the PAL System I is designed to provide a luminance

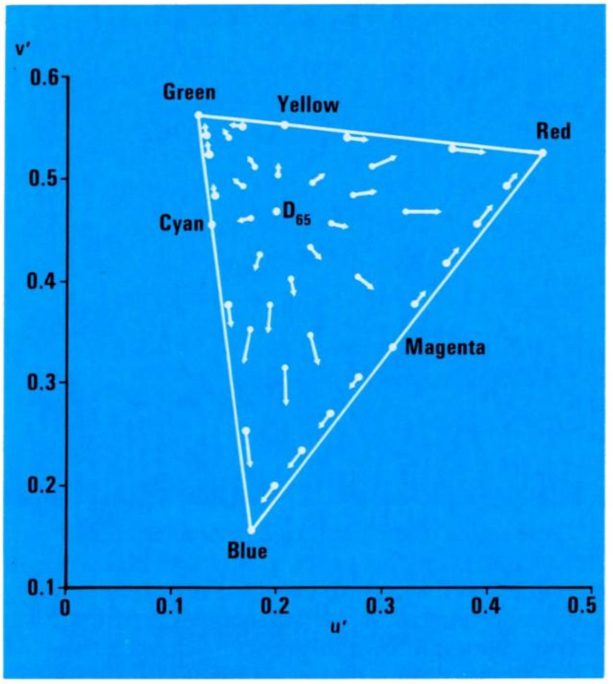


Fig. 7. Changes in chromaticity with an overall transfer characteristic of 1.26.

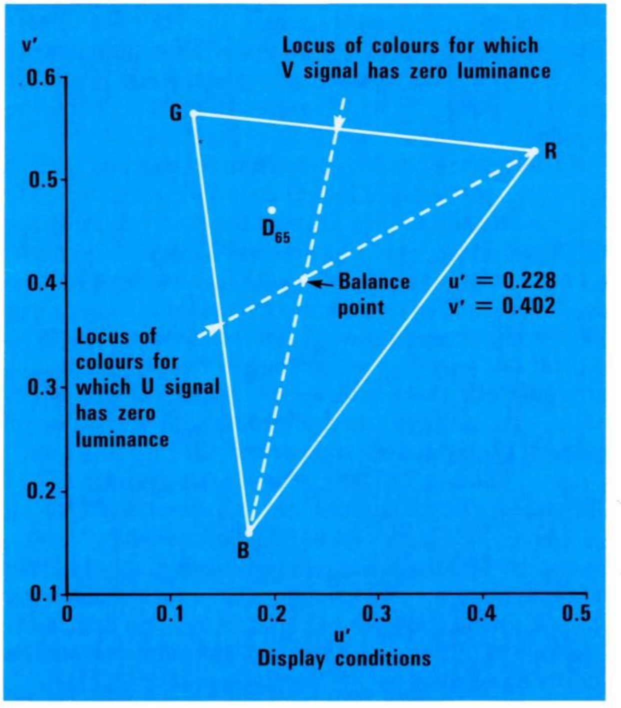


Fig. 8. Conditions giving zero-luminance colour-difference signals.

bandwidth of 5.5MHz and a chrominance bandwidth of only about 1.0MHz, waveform distortion can result from the imbalance. Although the effects are not normally of great significance, colour transitions involving rapid changes of luminance signal level can be impaired by overshoots. This is frequently observed in the television coverage of snooker games but perhaps a better example is the distortion that is manifest on the transition between the green and magenta areas of a colour bar test signal.

Constant Luminance

The principle of constant luminance in colour television requires that luminance information should be conveyed only by the luminance signal and that chrominance information should be conveyed only by the colour difference signals. It has been established that the PAL system violates this principle for two reasons as follows:

(i) The overall system is imbalanced by the use of NTSC relative luminance coefficients in the encoding and decoding process, with the display system and camera analysis based on PAL system chromaticities.

(ii) The use of gamma-corrected colour separation signals would, by itself, produce luminance information in the colour-difference channels, for all except neutral colours. In the PAL system, the effects of the gamma-corrected camera signals introduce variations in the amount of luminance information carried by the U and V signals, but the inherent imbalance of the system is 'cancelled out' at one particular chromaticity only. For all other colours, except neutral tones at D_{65}, the principle of constant luminance is violated to some extent.

Possibly the most important aspect of the failure of constant luminance concerns the compatible black and white picture. In a colour receiver, the luminance signal is used only to recover the gamma-corrected colour separation signals, (eg, $E'_Y+(E'_R-E'_Y)=E'_R$). However, in a black and white receiver, the luminance signal is required to drive the display tube and, except for neutral tones, use of gamma-corrected signals in its formation causes a reduction in the level of the reproduced luminance, which is most significant for highly saturated colours. The

normalised luminance of the display will be as follows:

$$L = (0.299E_R^{0.45} + 0.587E_G^{0.45} + 0.114E_B^{0.45})^{2.8}$$

For a grey or white scene, in which $E_R = E_G = E_B = E$, this equation becomes:

$$L = E^{1.26}$$

and the system provides the correct luminance values, appropriate to the overall transfer characteristic of 1.26. However, for a fully saturated green (for example), the displayed luminance will be given by:

$$L = (0.587E_G^{0.45})^{2.8} = 0.225E_G^{1.26}$$

instead of the correct NTSC value which is:

$0.587E_G^{1.26}$.

If E_G has the maximum normalised level of unity, the luminance will be reduced from the correct NTSC level of 58.7% to 22.5%. Similiar calculations for fully saturated red and blue signals show luminance reductions from 29.9% to 3.4% and from 11.4% to 0.2% respectively. These reductions are not correct for the PAL system, however, since the required display luminance must be related to the PAL system standards. To take account of the differences in the encoding and display relative luminance co-efficients, as well as the differences in the gamma-correction exponent and the display tube transfer characteristic, it is convenient to use the concept of a constant luminance index, k[3]:

$$k = \frac{(0.299E_R^{0.45} + 0.587E_G^{0.45} + 0.114E_B^{0.45})^{2.8}}{0.222E_R + 0.707E_G + 0.071E_B}$$

For any combination of colour separation signals, the constant luminance index expresses the normalised luminance of the display as a fraction of the true normalised luminance in the PAL system. Although the luminance is greatly reduced for fully saturated colours, calculation shows that quite a small degree of desaturation restores the luminance to a reasonably high proportion of the correct level.

Figure 9 shows the contours of chromaticities for a range of constant luminance indices between 1.0 and 0.6, on a u′, v′ diagram. This illustrates clearly how the luminance increases significantly with slight desaturation, since a very large proportion of the full colour gamut is contained within the contour k = 0.6.

In practice, a somewhat fortuitous factor helps to maintain reasonable luminance levels in black and white receivers. When saturated colous are encoded a correspondingly high amplitude of chrominance subcarrier is added to the luminance signal, as explained previously. The complete signal is applied to the grid/cathode circuit of the display tube. The positive half-cycles of subcarrier increase the light output to a greater extent than the reduction caused by the negative half-cycles, because the tube has a non-linear transfer characteristic ($\gamma = 2.8$, approximately). In effect, the subcarrier is partially rectified and the resulting dc component serves to increase the luminance output of the display tube. This effect is proportional to the colour saturation and the reduction in the constant luminance index is thus largely offset.

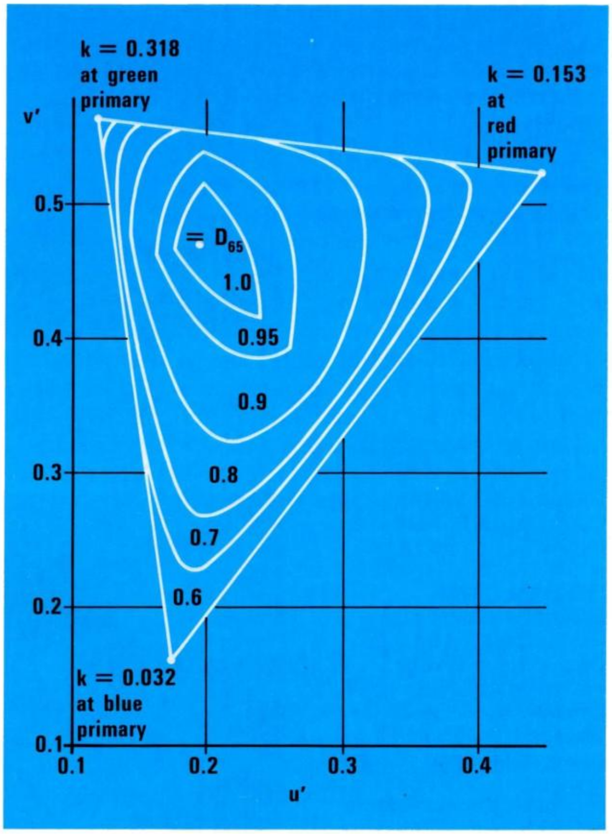


Fig. 9. Constant luminance index contours for the PAL system (Gamma = 1.26).

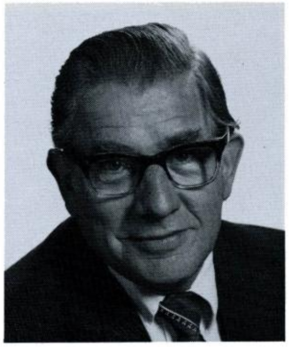
References

1. Hacking, K., 'Colorimetric Analysis of Interference in Colour Television, *BBC Monograph No. 60,* 1966.

2. Sproson, W.N., *Colour Science in Television and Display Systems*, **3**, 67-79, Adam Hilger Limited, Bristol 1983.

3. Livingston, D.C., *Proc. IRE, 42,* 138-150, 'Colorimetric Aspects of the NTSC Colour Television System' 1954.

PETER A. KING began his career in the retail television trade. He then worked as a development and production engineer, first for Rank Cintel and then for Pye TVT. He joined the IBA in 1970, and is currently Head of the Technical Facilities Unit at Crawley Court. He is married, has two sons and lives in Hampshire.



Computer-operated Spectrophotometric Analysis of Cameras (COSAC)

PETER J. MARSHALL C.Eng., MIERE, worked for the BBC from 1963 to 1967, first at Television News and then in the Designs Department. Joining the IBA's (then ITA) E&D Department in 1967 he worked on a number of projects concerned with the changeover to the 625-line system and the start of colour transmission before moving to the Quality Control Section. Since then he has held a number of posts in Quality Control and been concerned with such diverse fields as: subjective quality monitoring standards, improved methods for the measurement of acoustic reverberation time of studios, test methods for television components systems and the colorimetric evaluation of television cameras and monitors. He has recently taken up the post of Engineering Operations Manager at HTV.

by P. A. King and P. J. Marshall

Synopsis
A spectrophotometric method of measuring the colorimetric performance of TV colour cameras is discussed. A computer-operated system of measurement and analysis, developed by the IBA, is described in some detail. Examples of the results of comparing two cameras are expressed as a table of differences in luminance, saturation, chroma and hue, and the relationships to other relevant systems of units are given.

Measurement Methods

There are two principal ways of measuring the colour reproduction of a television camera. One is to place suitably illuminated test colours in front of the camera to determine the colour separation signal outputs (R, G, B) for each test colour. The second is the 'spectrophotometric' method in which monochromatic light is used to measure the spectral responses of the camera. From these the R, G and B output for each test colour may be computed using the spectral reflectance data of the colour and the spectral power distribution of the illuminant.

From the R, G, B levels, the colour of the display on a monitor is calculated. The difference between the displayed colour and the visual appearance of the test colour (making any correction necessary for the difference between the illumination and the television white point) is a measure of the colorimetric fidelity of the camera.

Each method has its advantages. The 'real-sample' method depends completely on careful illumination of the sample and on accurate alignment of the camera. It provides a quick and useful check of the mismatch between cameras. The spectrophotometric

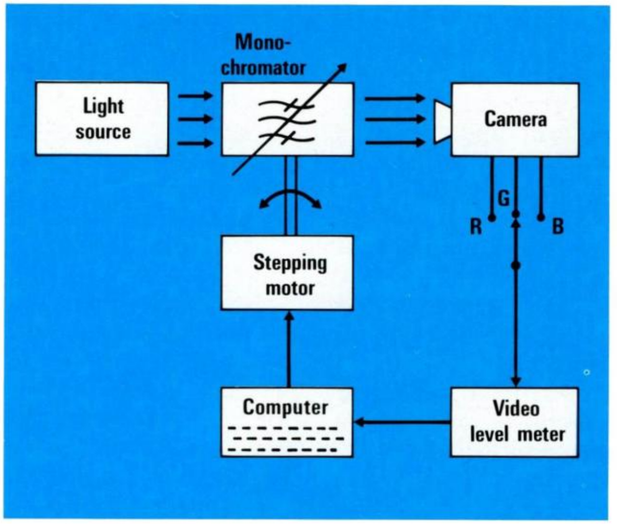


Fig. 1. A computer-operated system for measuring the colorimetric performance of a TV camera.

method is the more fundamental approach and the difficulties of accurate camera alignment can be avoided by performing the black and white balance of the camera in computation rather than in practice. Test colours are held as spectral reflectance data and hence do not suffer from damage or ageing. On the other hand, the calibration of the test equipment takes time and expertise and may well require outside help from a University or Standards Authority. A short explanation of the operation of spectrophotometers is contained in Appendix I while calibration techniques are discussed in Appendix 2.

Description of the IBA 'COSAC' Equipment

The schematic arrangement for camera measurement is shown in Fig. 1. The system is portable and uses readily available components, with the exception of simple computer interface cards to drive the stepping motor and take the output of the video level meter back into the computer.

To avoid inaccuracies due to flare or incorrect flare correction in the camera, the camera zoom lens is adjusted to make the image of the monochromator output port a small part of the picture area, and the flare correction is switched off. A hood shields the camera from extraneous light sources.

The light source is a quartz iodine lamp fed from a current-stabilised supply. Voltage stabilisation is less satisfactory since the voltage measurement is subject to variations in contact and lead resistance, contact potential and filament end effects.

The level meter is fed with the red, green or blue video output from the camera, as appropriate. The measuring marker, which identifies the area of the picture over which the level meter samples and integrates, is positioned within the picture area illuminated by the image of the monochrometer exit port. The level meter converts this level to binary coded decimal (BCD) and this value is read back into the computer for storage and processing.

Most television cameras use a 'linear matrix' to improve colour fidelity. In camera design, a fundamental compromise has to be reached between the bandwidth of the taking characteristics and the sensitivity of the camera for a given signal-to-noise ratio. Typical taking characteristics are shown in Fig. 2. A broad green taking response worsens the colour reproduction of the camera, desaturating and changing the hue of some colours. A linear matrix improves the accuracy of colour reproduction by adding small amounts of negative signal from each R G B channel into the others, before gamma correction.

With a pure spectral light, this subtraction could result in the signal being below black level at certain wavelengths so, to avoid black clipping, an abnormal amount of lift is introduced. In order that the signals shall not be applied to the gamma corrector at an improper level, measurement is carried out with the gamma set to unity. The lift is removed subsequently in calculation. The law of the gamma corrector is measured separately and gamma correction is applied by calculation at a later stage. The microprocessor makes short work of the measurements. Manual measurements would be taken mainly at 10nm intervals, with 5nm intervals only at the crossovers between the main lobes. With the computer, however, it is practicable to measure at every 1 nanometer (averaging every five readings) to increase accuracy, and still the readings are completed in five minutes. No attention is paid to the exact black or white balance of the camera since this is achieved more precisely in later computation. Measurements are made from the 5nm band centred on 380nm, through the visible spectrum, to the band centred on 760nm. Cameras have little or no response above 720 nm and the last five readings are used to provide a black level reference. The measurement scan is made three times, once for each of the red, green and blue camera outputs, scanning always in the same direction to avoid possible inaccuracies due to backlash in the mechanism.

Figure 2(a) shows the results obtained for a typical

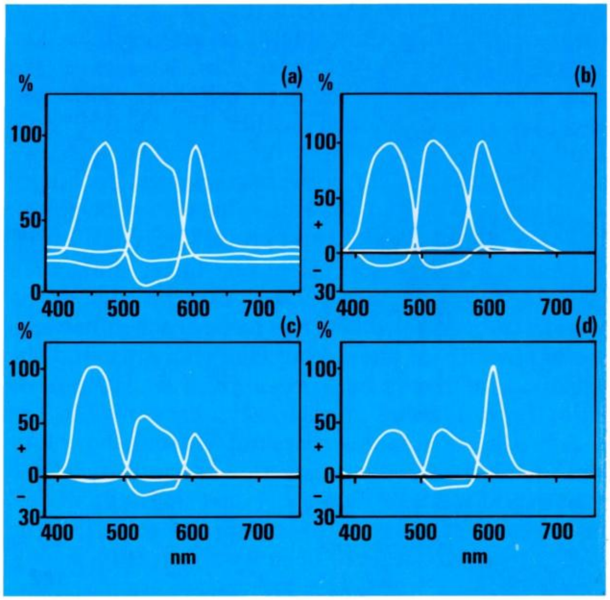


Fig. 2. The responses of a TV colour camera.
(a) As measured, and before correction.
(b) Black level corrected.
(c) Corrected for the characteristics of monochromator and lamp.
(d) True camera spectral sensitivities balanced for equi-energy white.

camera. The shape of the red negative response in the green spectral region shows clearly how it has been derived from the green signal tube.

Corrections for the Measuring Equipment and Scene Illuminant

As mentioned earlier, measurements are made with a considerable lift or brightness pedestal to avoid cutting off the negative lobes in the responses. This is corrected immediately by subtracting from each curve the appropriate lift value obtained at 750-760nm, where the camera has no response. The effect of this calculation is equivalent to performing black balance at the camera.

Once this is done (Fig. 2(b)) each of the curves is multiplied, wavelength by wavelength, by factors which correct for the spectral characteristics of the monochromator and light source. Figure 2(c) shows the responses after these corrections. As might be expected with an incandescent light source, measurements at the red end of the spectrum have had to be reduced considerably compared with those in the blue region.

The next stage in the analysis is to 'balance' the camera for the illuminant of the scene. Normally this would be taken as a colour temperature of 3100K, representing studio lighting, or D_{65} for outside broadcast use. The OB camera, of course, will have to cope with tungsten lighting, sunlight, overcast daylight and, from time to time, a mixture of daylight and artificial light sources in the same scene. A single matrix corrector for all occasions is a compromise. It is possible to calculate the nature of that compromise by considering each light source in turn.

The white balance of the camera for any illuminant can be achieved by a computation which imitates the camera gain adjustments required. It is necessary to multiply the red, green and blue curves by the spectral power distribution of the light source and then adjust the relative amplitudes of the red, green and blue responses, to equalise the areas under each curve. However, this cannot be done directly, since a gain adjustment in one channel will affect the response matrixed into the other channels. This difficulty is avoided by first removing the matrix in calculation, then balancing the camera as described above, and finally restoring the matrix. The matrix co-efficients can be derived from the curves by measuring the relative responses of the red, green and blue channels at three wavelengths where it is known that only one of the tubes will produce an output, and performing an algebraic matrix inversion, wavelength by wavelength.

The red, green and blue signals, stripped of their matrices, are then multiplied by the spectral response of the light source, wavelength by wavelength, the area under each curve is obtained by summation, and each value in the array is divided by the appropriate factor to equalise the areas. The matrix can then be restored using the inverse of the co-efficients previously derived (Fig. 2(d)). In practice, however, the calculations are minimised if the matrix is 'restored' after red, green and blue values have been calculated for particular colours. This stage in the analysis is now described.

If the spectral reflectance of a colour is multiplied, wavelength by wavelength, by the camera red, green and blue spectral sensitivity curves, the total area under each curve will provide values for red, green and blue which should be exactly the same as would be obtained from the camera red, green and blue head amplifier outputs, had the real colours been placed in front of the camera, suitably illuminated.

An example of the correlation between the methods is shown in Fig. 3. The general error in slope may be due to incorrect setting of white level arising

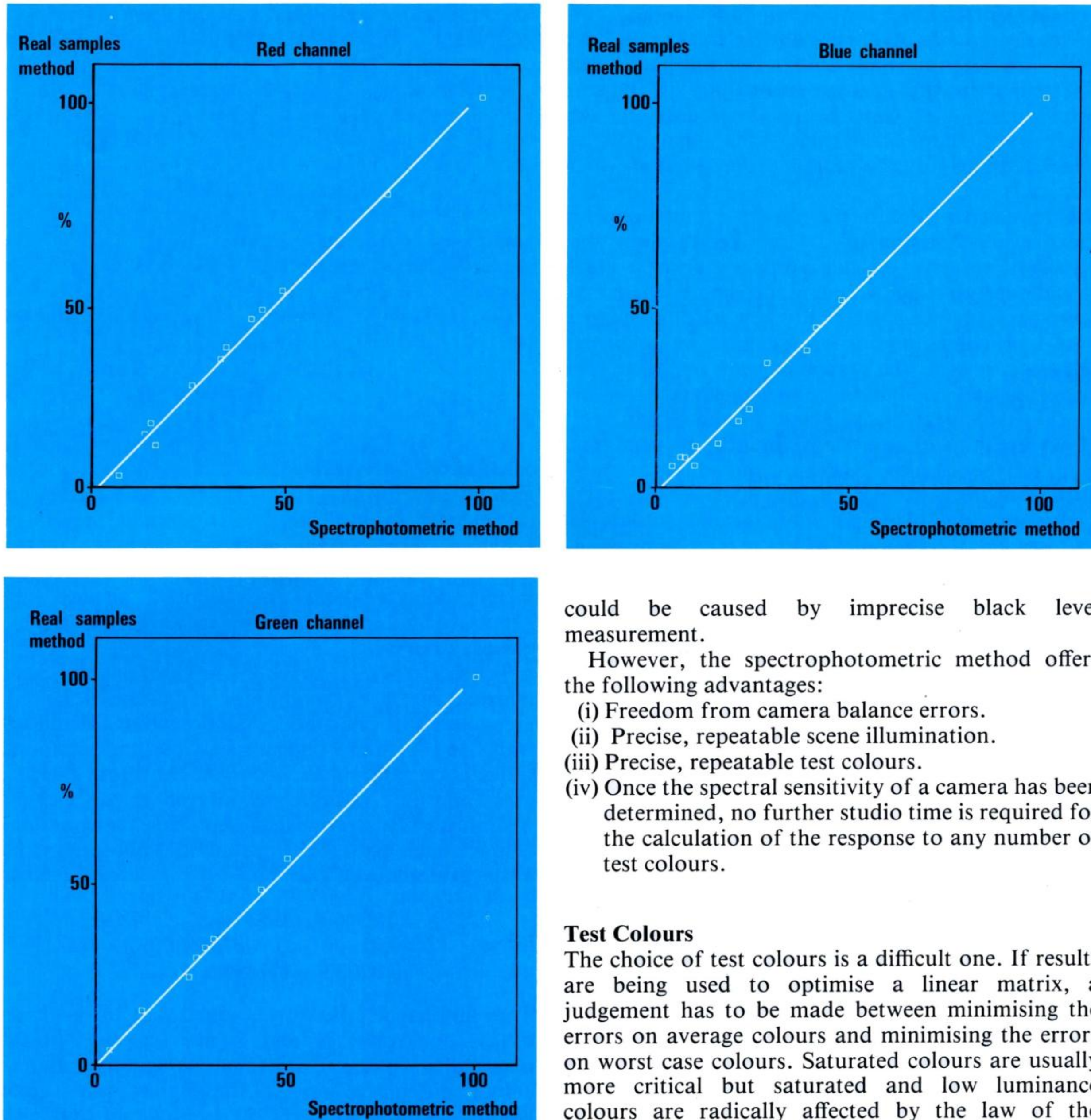


Fig. 3. The correlation of the R,G,B outputs measured by the direct sample method and by the spectrophotometric method for 14 test colours.

either from level measurement errors or from inaccurate estimation of the reflectance of the standard white. The non-zero value of the intercept could be caused by imprecise black level measurement.

However, the spectrophotometric method offers the following advantages:

(i) Freedom from camera balance errors.
(ii) Precise, repeatable scene illumination.
(iii) Precise, repeatable test colours.
(iv) Once the spectral sensitivity of a camera has been determined, no further studio time is required for the calculation of the response to any number of test colours.

Test Colours

The choice of test colours is a difficult one. If results are being used to optimise a linear matrix, a judgement has to be made between minimising the errors on average colours and minimising the errors on worst case colours. Saturated colours are usually more critical but saturated and low luminance colours are radically affected by the law of the gamma correction and may confuse the issue. There is no ideal solution. It is probably wise to place special emphasis on the results of skin tones. Test colours should include the primaries and complementaries at both high and medium levels of saturation. However, there is no point in having too many test colours - that only serves to make a difficult judgement impossible!

Gamma Correction

All measurements and analyses described so far have been carried out at unity gamma. However, limitations in the gamma correction law have a pronounced effect on colour reproduction. An analysis of these limitations is important to an understanding of the colour reproduction of a camera.

Gamma correction in the camera compensates for the transfer function of the receiver display tube. However, to achieve total compensation near black would need very high gain and this would worsen the noise performance and amplify any drift in the black level to a corresponding degree. In a monochrome television system, the maximum gain in the gamma corrector can be limited quite considerably before crushing of near-black detail becomes apparent. However, in a colour system, limiting the maximum gain of the gamma corrector introduces a more significant distortion; it has the effect of increasing the saturation of already highly saturated colours.

Consider, for example, a bright red colour which produces a red signal, before gamma correction, of 40% and green and blue signals of 3%. The red output of the gamma corrector will be approximately 66% and the green and blue outputs, being the input signal multipled by the maximum gain, will be 9% if the gain is three or 18% if the gain is six. The value of the green and blue signals after correction with a gamma of 0.45 would be 20.6%. Unfortunately, this effect is often disregarded and many of the latest cameras have gamma correctors where the maximum gain is no more than 2.5 or 3.

Mention has been made earlier that the IBA COSAC equipment applies gamma correction as a calculation based on separate measurements of a greyscale chart. With a choice of look-up tables, the effect on colour reproduction of varying the law of gamma-correction can be demonstrated easily.

An interesting technique is adopted in some hand-held cameras which are specifically intended for news coverage. In order to avoid the above problem, while maintaining the best possible signal-to-noise ratio, some camera designs employ matrix correction after the gamma corrector. This has the effect of lessening the correction for saturated colours and might for this reason seem very desirable. To a degree, it does undoubtedly work but improvement in the worst case is made at the expense of the general case, and the average fidelity of colours in these cameras is never as good as it could be if conventional means were adopted. Nevertheless, in circumstances where the low-light performance of the camera is of paramount importance, such a non-linear matrix is much better than no matrix at all.

The calculations discussed so far yield the camera R, G, B outputs for each test colour. However to compare television reproduction with the visual appearance of the test colours, it is necessary to allow for the gamma of the display tube.

Television systems normally have an overall gamma exceeding unity; in fact, with a display tube gamma of approximately 2.8 and correction in the camera of approximately 0.45, the overall gamma is about 1.26. The reasons for this are discussed in the previous chapter.

The general effect of high overall gamma in colour television is to increase the saturation and, for certain colours, a hue shift may occur as well.

To simulate the process of reproduction, gamma calculation for the display tube should employ a gamma law of 2.8. However, this will mean that completely faithful reproduction will never be achieved. For certain analyses, such as matrix optimisation studies, it may be better to ignore this system deficiency and to assume a display tube gamma of 2.2 corresponding to an overall system gamma of unity.

The CIE 1976 L u v Uniform Chromaticity Scale affords a means of comparing the figures for the red, green and blue phosphor excitations thus calculated, with the visual appearance of the colours. Calculation takes place in two stages. From the red, green and blue values previously obtained, X, Y, Z tristimulus values are calculated using the equations below, which assume the use of EBU phosphors and a white reference of D_{65}.

$$
\begin{aligned}
X &= 0.4306\,R + 0.3416\,G + 0.1782\,B \\
Y &= 0.2220\,R + 0.7067\,G + 0.0713\,B \\
Z &= 0.0202\,R + 0.1296\,G + 0.9392\,B
\end{aligned}
$$

The luminance, Y, forms one axis in a three-dimensional plot; X and Z are the axes in the chromaticity plane. Unfortunately, equally apparent colour differences do not have the same vector lengths in different parts of the diagram and so a further conversion is made to produce the widely adopted L, u′, v′ co-ordinates where:

$$
u' = \frac{4X}{X+15Y+3Z} \qquad v' = \frac{9Y}{X+15Y+3Z}
$$

A fuller account of the CIE system is given in the chapter on 'Colorimetry' (page 16).

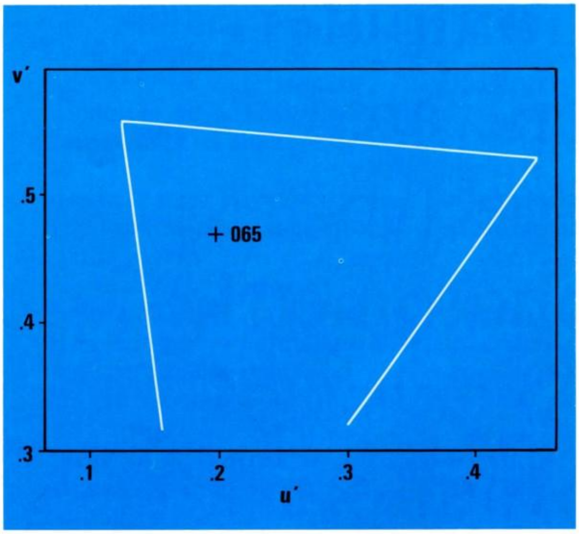


Fig. 4. The results of a typical COSAC analysis.

Results

Figure 4 shows a typical result of computer analysis. A lightweight camera is being compared with a general-purpose outside broadcast camera. D_{65} illumination is assumed and this analysis is made for a set of 12 highly saturated colours. The differences between results for the two cameras are tabulated as follows:

ΔY_C is the luminance difference

ΔS_C ΔH_C are the saturation and hue differences calculated as the radial and tangential differences between the u′ v′ addresses for the two cameras

ΔC_C is the overall chrominance difference $= (\Delta S_C{}^2 + \Delta H_C{}^2)^{\frac{1}{2}}$

ΔE_C is the three-dimensional vector difference $= (\Delta C_C{}^2 + \Delta Y_C{}^2)^{\frac{1}{2}}$

The symbol 'C' identifies IBA COSAC units where ΔS_C and ΔH_C have been multiplied by a constant factor of 400 to give similar significance to chrominance and luminance differences. Finally, the u′ v′ results are plotted to show the balance of the errors at a glance.

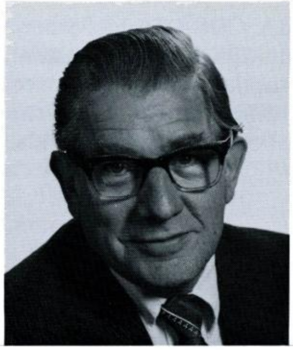
Colour Perception

The COSAC units of saturation, hue, chrominance and overall difference are objective measures intended to represent the relative magnitudes of the various attributes. However, colour perception is not a direct function of chrominance. It is, for example, modified by the luminance level and this function can be incorporated in a calculation to produce units of 'perceived colourfulness'. But the eye-brain combination is a more complex system to model than this. The COSAC units of perceptual colour difference have been developed solely to identify the most significant differences of luminance, saturation and hue between one camera and another, so that the appropriate area of camera performance to be modified (gamma-corrector or matrix) may be identified.

References

1. Hunt, R. W. G., 'A Model of Colour Vision for Predicting Colour Appearance', *Colour Research and Application*, Volume 7, No. 2, Part 1, Summer 1982.

2. Judd and Wyszecki., 'Colour in Business', *Science and Industry,* Wiley 1963.



PETER A. KING
A biographical note appears on page 40.

PETER J. MARSHALL
C.Eng., MIERE.
A biographical note appears on page 40.

Computer-operated Spectrophotometric Analysis of Monitors (COSAM)

by P. A. King and P. J. Marshall

Synopsis
A computerised spectrophotometric method of analysing and comparing the colorimetric performance of TV colour monitors is described. The results may be expressed as tristimulus or CIE chromaticity co-ordinates. Some of the sources of errors affecting these measurements are discussed.

The chromaticity of a light source may be calculated from measurement of its spectral power distribution (SPD) over the visible band. The spectrophotmetric measurement of the spectral power of a luminous source can employ a method broadly similar to that used for spectrophotometric measurement of cameras described in the previous chapter (COSAC).

Figure 1 shows that a small part of the spectrum which is radiated by the monitor is passed to the photo-electric-cell by the monochromator. The analogue-to-digital converter relays the received level to the microcomputer for storage. Then the stepping motor is advanced to tune the monochromator to a new wavelength and the process is repeated.

The results must be corrected for four effects:

1. ANY ADC ZERO OFFSET. This may be determined from the average of a number of readings near 760nm, if it is known that the luminous source has no output at that wavelength, or by capping the monochromator inlet port. Correction is by subtraction of the offset from each reading.

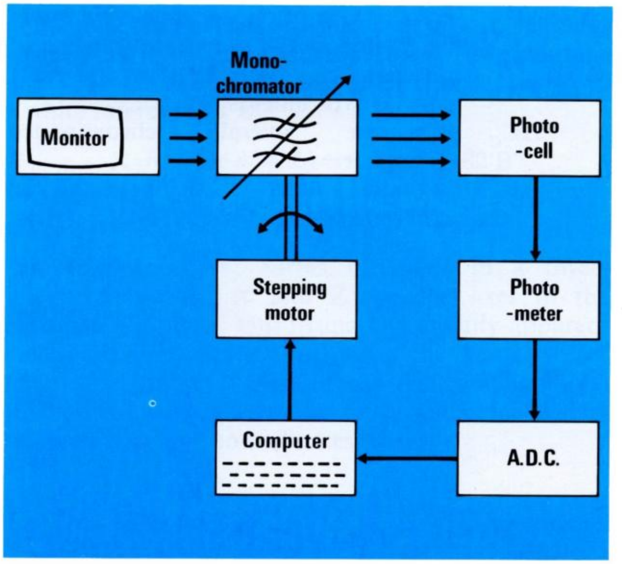


Fig. 1. A computer-controlled system used to analyse the colorimetric performance of TV monitors.

2. SPECTRAL POWER TRANSFER EFFICIENCY OF THE MONOCHROMATOR. The variation in the monochromator's insertion loss over the spectrum is considerable. Relative to the maximum output (usually at about 500nm), the output falls to about 10% at blue and to some 40% at red.
3. SPECTRAL SENSITIVITY OF THE PHOTO-ELECTRIC CELL. The type of photo-electric cell used is the main factor governing spectral sensitivity. Silicon cells are relatively insensitive to blue whereas tri-alkali photomultipliers are less sensitive to red. However photomultipliers have good linearity and very high gain and are therefore quite suitable for this application.
4. CORRECTION OF MONOCHROMATOR WAVELENGTH CALIBRATION. Correction for factors 2 and 3 is applied by multiplying each result by a factor appropriate to the wavelength. The derivation of the calibrations required is given in Appendix 2.

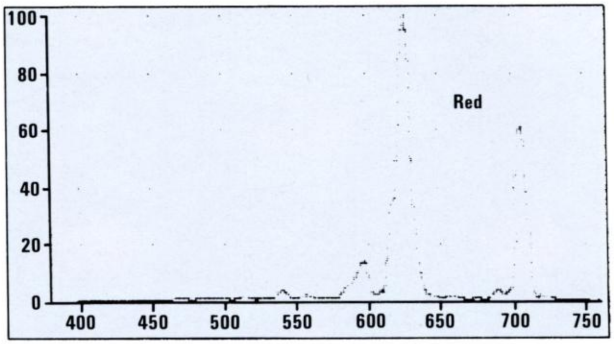


Fig. 2(a). The spectrum emitted by a typical red phosphor.

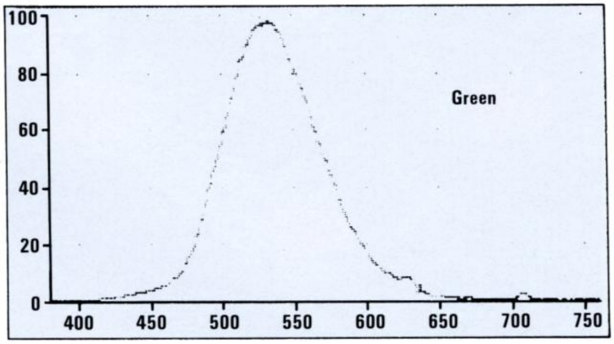


Fig. 2(b). The spectrum emitted by a typical green phosphor.

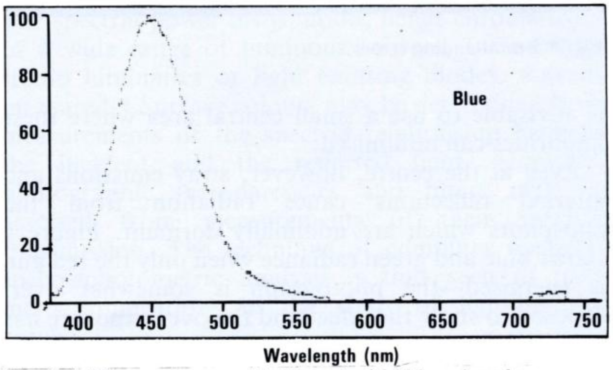


Fig. 2(c). The spectrum emitted by a typical blue phosphor.

Choice of Monochromator Bandwidth and Measuring Interval

For the measurement of colours where the SPD changes slowly across the visible spectrum, the half-amplitude bandwidth of the monochromator need not be smaller than say 10nm and the wavelength interval of measurement may be similar.

However if the SPD of the source is concentrated into a small band, such as a gas line, then the use of a wide bandwidth will result in a measured SPD of greater width than the radiant SPD if the measuring wavelength intervals are sufficiently fine. Although the dominant wavelength will be correctly assessed the purity will then be underestimated.

Hence for radiant SPD's of a spiky nature, a narrow half-amplitude bandwidth should be used but, unless the wavelength intervals of measurement are suitably close, there is a chance that a spike might be missed or underestimated and displaced. Thus the measured purity could be correct but the dominant wavelength might be incorrectly assessed.

The blue and green phosphors of monitors have generally a fairly smoothly distributed SPD but that of the red phosphor consists of a number of narrow spikes, as shown in Figs. 2 a, b and c. Within the measurement accuracy which is required for monitors, a suitable half-amplitude bandwidth is 4nm with wavelength measuring intervals of 1nm to 5nm.

Taking the visible band as 380nm to 760nm, reading at 1nm intervals implies 381 measurements - a daunting task if performed manually but not if performed automatically.

Choice of Screen Position to be Measured

Beam-landing errors cause unwanted excitation of adjacent phosphors by an electron stream intended for a particular phosphor, as shown in Fig.3. This colour impurity is less a function of the CRT than of scan coils and adjustment procedure so if the intrinsic phosphor chromaticity is to be measured, it

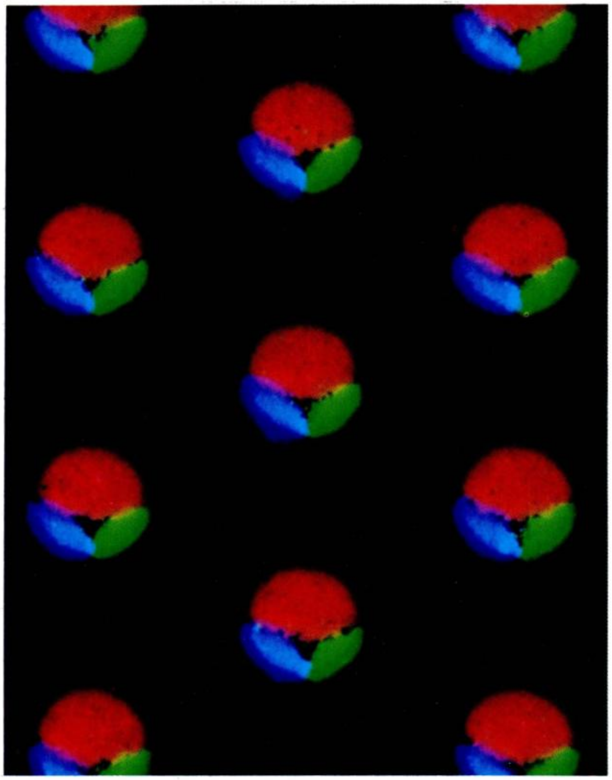


Fig. 3. Beam-landing errors.

is advisable to use a small central area where these impurities can minimised.

Even at the centre, however, stray emissions and internal reflections cause radiation from the phosphors which are nominally dormant. Figure 4 shows blue and green radiance when only the red gun is energised—the photograph is somewhat over-exposed to show the effect and the over-exposure has distorted the red colour. Note that in contrast to Fig. 3 all of the green and all of the blue phosphor area is energised.

This could be ignored by measuring just one phosphor dot but, since it is visible to the eye, this dilution should be included in the measurement.

Thus, to take phantom emission into account but to avoid assessing impurity, a central area of about 20mm high by 10mm wide should be measured.

Choice of Measurement Timing

Since television is a scanning system, any elemental part of the monitor screen area has excitation from the electron beam for only a brief period. For the remainder of the television picture repetition interval the elemental part afterglows, its light output falling at a rate inversely proportional to the phosphor persistence. The excitation-afterglow cycle is then repeated.

Phosphors may exhibit somewhat different colours at different parts of the excitation-afterglow cycle.

One approach to measurement would be to lock the measuring frequency to that of the television excitation-afterglow cycle and then suitable phase adjustment would enable measurement at any part of the cycle.

However the appearance of the phosphor is based upon the average colour so it is appropriate to let the measuring frequency free-run and to take the average of a large number of readings. Some five or ten readings at each wavelength interval brings the number of measurements up to 1,900 or 3,800—figures still quite manageable by automatic methods.

Noise Errors

Noise in the system is produced from several sources. The phosphor light output will be modulated by

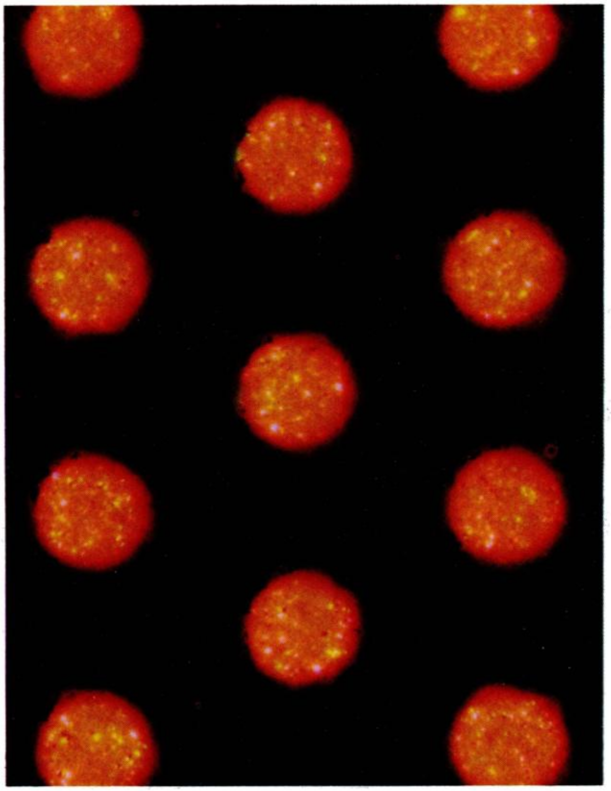


Fig. 4. An illustration of phantom emission.

noise arising from the monitor circuitry and the C.R.T. itself. Further sources are the phomultiplier and the subsequent amplifier.

Using 1mm slits in the monochromator and examining a screen area of 200mm^2 at a beam current set for normal viewing, produces a signal-to-noise ratio at the ADC input of some 30dB. Some form of noise reduction is required to improve accuracy and allow for the use of smaller monochromator slit widths, smaller measured areas and reduced beam currents.

The averaging dictated by measurement timing considerations also has the required effect of noise reduction.

Linearity Distortion

Examining a small part of the monitor screen results in a peak photomultiplier current many times greater than the mean current since the phosphor area under examination is excited for only a small part of the scanning cycle. For this reason special precautions to stabilise the dynode potentials and to linearise the photometer current amplifier are essential.

Calculation of Results

After correction for monochromator wavelength calibration errors, ADC zero offset, monochromator spectral power transfer efficiency and photomultiplier spectral sensitivity, the relative spectral power distribution of the source is obtained. Let the data be described as P

The tristimulus values X, Y, Z may then be calculated as follows:

$$X = \int_{380}^{760} P_\lambda \bar{x}(\lambda) d\lambda$$

$$Y = \int_{380}^{760} P_\lambda \bar{y}(\lambda) d\lambda$$

$$Z = \int_{380}^{760} P_\lambda \bar{z}(\lambda) d\lambda$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the CIE colour matching functions. Transposing to CIE chromaticity co-ordinates, in accordance with the relationships explained in the second chapter in this volume:

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z}$$

$$u = \frac{4X}{X+15Y+3Z}, \qquad v = \frac{6Y}{X+15Y+3Z}$$

$$u' = \frac{4X}{X+15Y+3Z}, \qquad v' = \frac{9Y}{X+15Y+3Z}$$

Use of Results

A common application of measurement is to establish monitor phosphor chromaticities relative to the EBU specification contained in EBU Tech 3213, which defines tolerance limits appropriate for broadcast quality assessment.

Other Applications of the Technique

The spectral power distribution, hence chromaticity, of a wide range of luminous sources, for example studio luminaires or light emitting diodes, may be measured.* Surface colours may be determined from measurements of the spectral relationship between the incident and the reflected light. Similarly, photographic transparencies and filters may be assessed from measurements of their spectral transmission. The technique of computer operated spectrophotometric analysis is thus seen to have many applications in the study of lighting and colour.

* Link Electronics of Andover (UK) have been licensed by the IBA to use the COSAM and COSAC systems.

APPENDICES

The following two Appendices refer to the articles by P. A. King and P. J. Marshall.

APPENDIX 1

THE MONOCHROMATOR

Spectrophotometry involves the measurement of light in a number of spectral bands.

It requires some form of spectral selector which, from a broad input spectrum, passes only a tuneable narrow band of light (i.e. monochromatic light). The monochromator is an instrument in common use for this purpose and several types exist. Monochromators may use a prism or a grating; gratings may be machine-ruled or holographic, transmissive or reflective, blazed or unblazed as well as flat or concave. Whatever the form, the principle of operation is to introduce an optical path length difference so as to create interference phenomena in the output. Only at wavelengths for which the interference is constructive will there be an output.

In the figure, two elements of a reflective diffraction grating are shown at a spacing d, the inverse of the grating pitch.

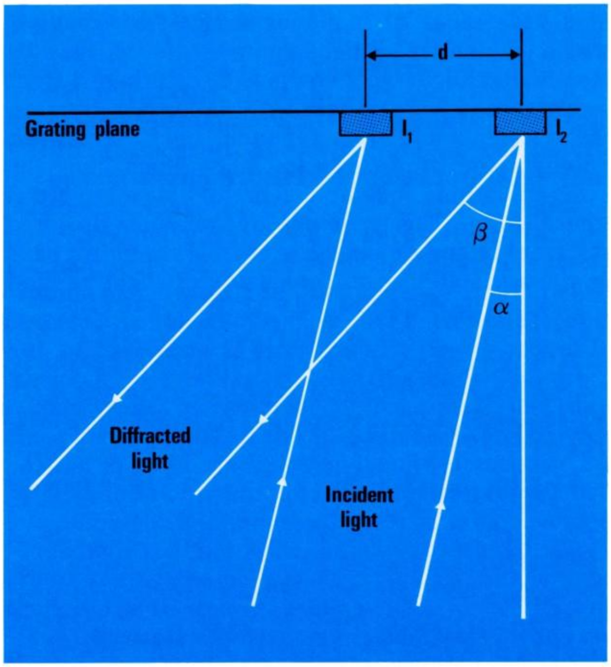


Fig. 1. The paths of rays before and after constructive diffraction from two rulings on a grating.

Let the light incident upon the grating be a parallel beam of monochromatic light (of wavelength λ) making an angle α with a line normal to the grating surface. Let the output be taken at an angle β to the normal.

The path lengths from the source to the grating elements differ by $d.\sin\alpha$. Similarly, the path lengths from the grating elements to the output port differ by $d.\sin\beta$.

The total path length difference (ΔL) is thus $d(\sin\alpha + \sin\beta)$ for these two grating elements and for all others (assuming α, β and d are constant). If ΔL equals an integral number (positive or negative) of wavelengths of the incident light, the interference will be constructive. Maxima of output intensity are given at any wavelength satisfying the equation:

$$\lambda = \frac{\Delta L}{N}$$

where N is a positive or negative integer.

Since variation of the angle β alters the wavelength at which a maximum occurs, it can be concluded that incident light is dispersed by the grating to form a spectrum; each value of N resulting in a separate spectrum.

The value of N indicates the 'order' at which the monochromator operates. In zero order ($N = O$) no spectral dispersion occurs and all incident wavelengths appear at the output.

In order to improve efficiency, the radiant flux may be concentrated to a particular order by 'blazing' the grating (Fig. 2).

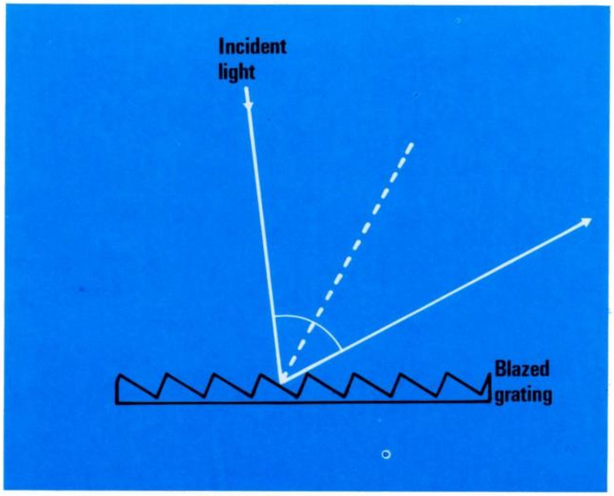


Fig. 2. A blazed grating.

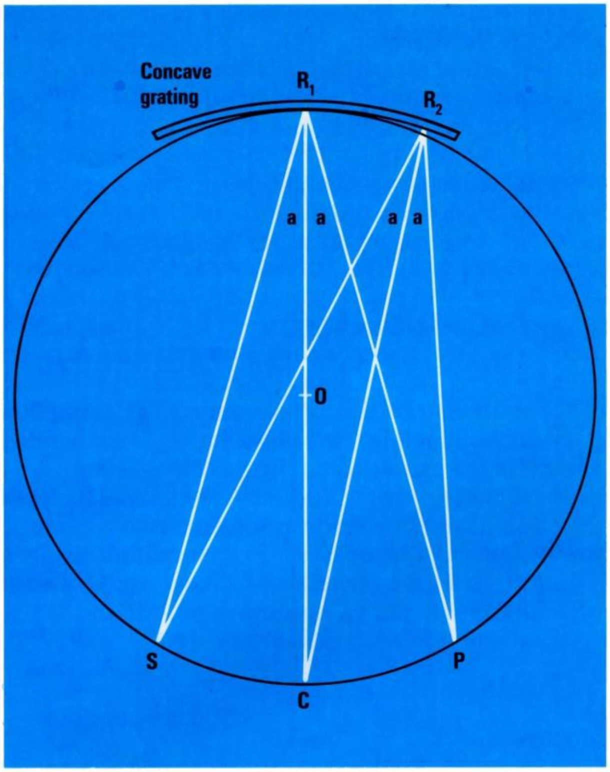


Fig. 3. The Rowland circle.

The principle is to tilt the elements with respect to the surface of the grating. The 'blaze angle' equals the angle of tilt and is generally chosen to maximise the output in first order. The outputs in other orders (including zero order) are reduced so that it becomes possible to use the monochromator over a wavelength range of 2:1 centred upon the 'blaze wavelength'.

A significant defect in the monochromator so far described is the need for collimating and imaging lenses, which introduce aberration and limit the range of wavelengths over which the instrument can produce a useful output. To overcome these problems, Rowland proposed construction of the grating on a concave mirror.

If the entrance slit (S) is located on a circle whose diameter equals the radius of curvature of the mirror, as shown in Fig. 3, the line RC is always normal to the surface of the mirror, regardless of the position of R. It follows that all the rays of light from S pass through the point P as shown. If grating lines are ruled on the surface of the mirror, sharp spectra will be formed on the circumference of the circle and, by positioning the exit port P in the appropriate place the desired order can be selected.

As previously mentioned, a variety of types of monochromator are available, each type having particular attributes. A full comparison of these would be out of place here but for colorimetry in television holographic curved gratings seem to be appropriate. Holographic gratings have a lower stray light ouput level than machine-ruled ones as a result of better uniformity of grating while curved gratings do not require collimating or focusing optics if used in the Rowland circle configuration.

The monochromator used by the IBA for colorimetric analysis applied to television is shown diagramatically in Fig. 4.

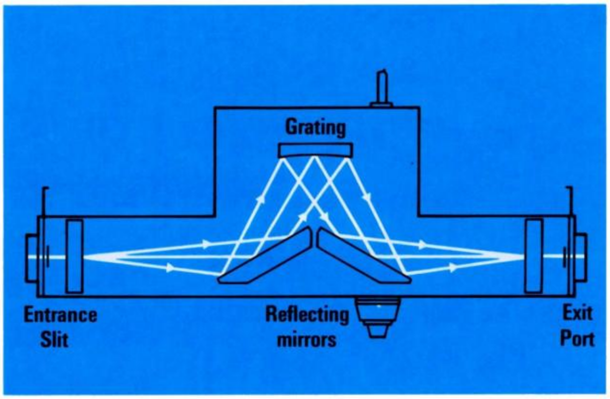


Fig. 4. A suitable monochromator.

Light from the entrance slit is reflected onto a concave grating. Part of the dispersed spectrum passes though the exit slit and therefore the width of that slit affects the width of the pass band as well as the power output. Rotation of the grating about an axis perpendicular to the plane of the paper, alters the part of the dispersed spectrum which aligns with the exit slit and thus tunes the monochromator to different wavelengths.

APPENDIX 2

CALIBRATION OF THE MEASURING EQUIPMENT

Polarisation

The monochromator output is highly polarised at certain wavelengths (Fig.1) and this polarisation has to be removed because light of different polarity is handled differently by the dichroic splitter in the camera.

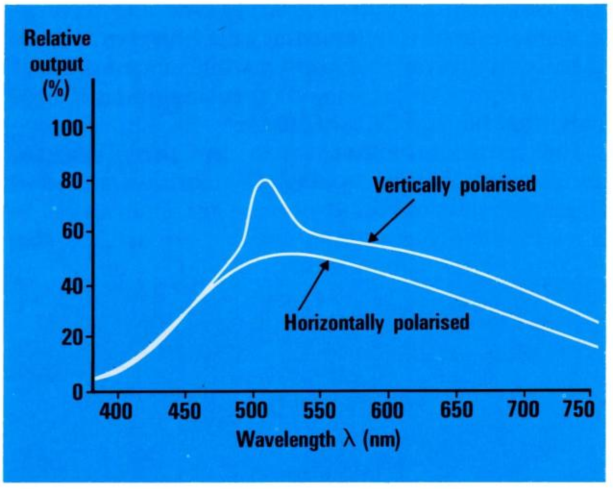


Fig. 1. The vertically and horizontally polarised light outputs from a monochromator illuminated with equi-energy light.

The polarisation can be reduced by fitting an opal glass diffuser in the monochromator exit port. A compromise has to be made between the extent of the diffusion and the loss of output intensity. The glass itself will also restrict the usable bandwidths to a small extent. An acceptable solution has been found, with the polarisation satisfactorily reduced.

Wavelength Calibration

The monochromator grating is rotated by means of a lead screw and sine bar to achieve a linear relationship between the lead screw rotation and the wavelength emitted. If this mechanism is not correctly adjusted then the wavelength of the centre of the pass band will not correspond to the reading on the dial.

Calibration is carried out using gas spectra of known wavelengths. When current is passed through a discharge lamp, atoms are excited, causing the electrons to jump from their normal ground-state energy levels to higher levels. On their return, the difference in energy, E_p, between the two levels, is released as a photon of frequency:

$$f = (E_p/h) \text{ Hz, where h is Planck's constant}$$

Light, emitted as a result of these electron transitions between different energy levels, forms a series of discrete spectral lines, each of known wavelength.

$$\lambda = h.c/E_p \text{ metres, where c is the velocity of light}$$

Three discharge lamps, mercury (Hg), cadmium (Cd) and helium (He), were chosen, to give a number of lines in the wavelength range, 346nm–730nm.

The monochromator under test is placed directly in the beam of light emitted by the discharge lamp. The wavelength setting of the monochromator is then adjusted in 0.1nm increments, about the expected wavelengths of known spectral lines for the lamp, until a maximum reading is obtained.

Table 1 shows the results for a typical monochromator.

TABLE 1

WAVELENGTH nm	ERROR nm	WAVELENGTH nm	ERROR nm
Cd 346.6	−0.2	Hg 404.1	−0.6
361.1	−0.3	546.5	+0.4
467.8	−0.1	He 587.7	+0.1
480.0	−0.2	668.7	+0.9
508.6	0	707.7	+1.2
643.8	+0.8	729.6	+1.5

Measurement of Monochromator Passband

The passband is a function of the width of the slits at the entrance and exit ports. Three slits, of 0.5mm, 1mm and 2mm width are available giving nominal half-amplitude bandwidths of 2nm, 4nm and 8nm. The bandwidth is one of the principal factors which determine the spectral power transfer efficiency of the monochromator.

The bandwidth is measured at a number of wavelengths using the same gas lines that are used for wavelength calibration. The monochromator is advanced in 0.1nm increments across each gas line and the output of the photoelectric cell is recorded at each increment.

Spectral Power Transfer Efficiency

The spectral power transfer efficiency (SPTE) is the ratio of the output power within a specified bandwidth to the input power within that bandwidth. A number of techniques are available to determine the monochromator's SPTE. For example, it is possible to use a calibrated standard lamp as the source, and a calibrated detector to measure the monochromator output, provided that absolute reliance can be placed on the calibration of the lamp and detector. The IBA method uses this technique to obtain confirmation of the results but a different procedure, using two monochromators, is used to make the initial measurements.

Firstly, the response of each monochromator is measured in the following manner.

A lamp, whose spectral power distribution, I_λ, need not be known, supplies light to the monochromator under test; the output of the monochromator, P_λ, is measured by a PEC whose spectral sensitivity need not be known.

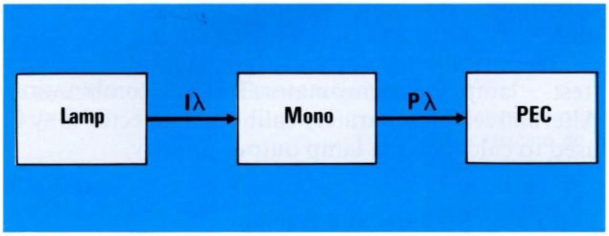


Fig. 2. The system used for the first stage of monochromator calibration.

The SPTE is proportional to the area enclosed by the transmission characteristic, which is of triangular shape. Thus, for a monochromator having half-amplitude bandwidth A and peak transmission L:

$$\mathrm{SPTE}_1 = \mathrm{kLA}, \text{ where k is a constant}$$

The straight line equation for the first half of the response is given by:

$$y_1 = \frac{L}{A}\lambda + L$$

Similarly, for another monochromator of half-amplitude bandwidth B, peak response M the first half response y_2 is:

$$\mathrm{SPTE}_2 = \mathrm{kMB}$$

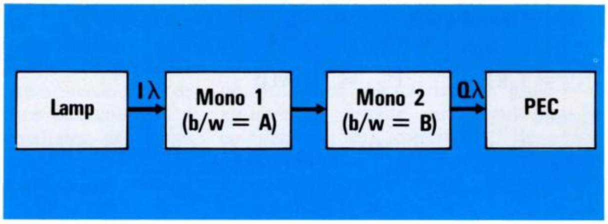


Fig. 3. The system used for the second stage of monochromator calibration.

$$y_2 = \frac{M}{B}\lambda + M$$

Next, the two monochromators are placed in series between the lamp and the PEC, and tuned to the same wavelength. The output power of the combination, Q_λ, is proportional to the integrand of the product of the individual responses:

$$Q_\lambda = I_\lambda 2 \int_{-A}^{0} y_1 y_2 \, d\lambda$$

$$Q_\lambda = I_\lambda \, \mathrm{LMA}\,(1 - A/3B)$$

The situation is illustrated in Fig.4, in which the shaded area represents the output.

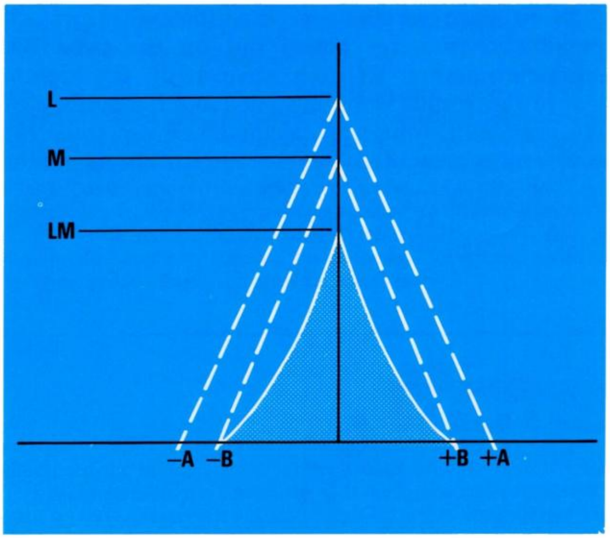


Fig. 4. The outputs from two monochromators are represented by the triangles −A, L, +A and −B, M, +B (where L and M are each less than 1). When the monochromators are used in series the resultant output is represented by the shaded area.

Considering each monochromator separately:

$P_{1\lambda} = I_\lambda kLA \qquad P_{2\lambda} = I_\lambda kMB$

Hence

$$Q_\lambda = \frac{P_{1\lambda}M(1-A/3B)}{k} \qquad Q_\lambda = \frac{P_{2\lambda}LA(1-A/3B)}{kB}$$

But $\quad SPTE_2 = kMB \qquad SPTE_1 = kLA$

Therefore

$$SPTE_2 = \frac{Q_\lambda k^2 B}{P_{1\lambda}(1-A/3B)} \qquad SPTE_1 = \frac{Q_\lambda k^2 B}{P_{2\lambda}(1-A/3B)}$$

The SPTE need not be known in absolute terms, since only the relative response from wavelength to wavelength is significant. Therefore, the constant, k, may be assigned a value of unity.

It should be noted that the spectral power distribution of the illuminant and the spectral response of the PEC are common throughout these measurements and may be disregarded since the solutions involve the ratio Q_λ/P_λ.

As three slit widths are available for each monochromator, nine different tests can be carried out. Exchanging the monochromator positions gives a further nine possibilities and, since each test produces results for both monochromators, it can be seen that six results are possible for each monochromator/slit width combination.

In an effort to eliminate experimental errors, all possible tests were carried out on the two IBA monochromators. At each wavelength, the highest and lowest results were discarded and the average of the remaining four was calculated. From that, for each monochromator, the average for all slit widths was calculated. The difference between the result for each slit width and the overall average was calculated and then smoothed to remove perturbations due to noise and quantisation effects. Finally, the smoothed differences were added back to the average for all slits so as to derive final smoothed figures for each monochromator/slit-width combination.

Optical measurements of this kind are notorious for the difficulty of getting repeatable results. Painstaking cross-checks and refinements may make only a small difference to the calculated results for a camera, but the high degree of conformity of calibrations adds significantly to the confidence which can be placed on the results.

Determination of Lamp and PEC Responses

Once the spectral power transfer efficiency of the monochromator has been determined, the spectral sensitivity of the PEC can be calculated by measuring the overall response of a 'standard lamp/monochromator/PEC' combination and correcting for the known responses of the monochromator and the standard lamp.

The portable test lamp is then calibrated, using a 'test lamp/monochromator/PEC' combination. Alternatively, a separately calibrated detector may be used to calculate the lamp output directly.

Test Lamp Stability and Ageing

Little experience of the long-term stability of the measuring equipment has yet been gained. However, commonsense suggests that the lamp will age and so regular checks of the 'lamp/monochromator/PEC' response against previous figures are made and the necessary corrections are applied.

La mesure de la lumière
par Prof. R.W.G. Hunt et P.J. Darby

Résumé

La photométrie utilise la réponse de l'œil humain à différentes longueurs d'onde de lumière pour établir un système d'unités photométriques qui se rapportent directement aux unités radiométriques utilisées en physique. A partir de cette base, on définit des unités pour la mesure du flux lumineux, de l'intensité lumineuse, de l'éclairement, de la luminance, de l'efficacité lumineuse, de l'exposition à la lumière et de la réfringence. Alors que la photométrie se penche sur l'effet visuel de la lumière, la spectrophotométrie relève la quantité de lumière à chaque longueur d'onde et fournit des méthodes de mesure qui conviennent à l'étude des phénomènes de la couleur. On décrit une méthode pour la mesure de la distribution de la puissance spectrale des sources lumineuses, qui est suivie par une description des conditions normalisées de la C.I.E. pour la mesure du facteur de réflexion spectrale et de transmission spectrale. Ce chapitre se termine avec une discussion sur les sources lumineuses, y compris la loi de Planck sur les radiations, le concept de thermocouleur et les définitions des illuminants normalisés de la C.I.E.

Colorimétrie
par Prof. R.W.G. Hunt

Résumé

La colorimétrie est fondée sur le principe qui établit que les observateurs peuvent assortir des couleurs avec des mélanges additifs de couleurs de trois stimuli de référence dans des quantités définies comme valeurs trichromatiques. Au moyen des stimuli de référence à certaines longueurs d'onde, la CIE a défini une série normalisée de valeurs trichromatiques qui correspondent à chaque longueur d'onde du spectre, et ces données constituent le '1931 colorimetric observer' (observateur colorimétrique 1931) normalisé. Afin d'éviter toutes valeurs trichromatiques négatives, on a établi une nouvelle série de fonctions correspondantes aux couleurs à partir des données normalisées, exprimées par les valeurs imaginaires X, Y et Z. Les proportions de valeurs primaires utilisées dans un assortiment de couleurs s'appellent coordonnées trichromatiques, et elles peuvent être tracées sur un diagramme de chromaticité ou sur une carte des couleurs. Afin d'obtenir un diagramme qui permette la réalisation d'une échelle raisonnablement uniforme par rapport aux changements de couleurs perçus, on a introduit le système CIELUV 1976 en utilisant des axes modifiés que l'on a appelé 'u et v'. Les formules de différence de couleur doivent tenir compte de la luminance et de la chromaticité et, par conséquent, elles nécessitent trois dimensions. La CIE a préconisé deux espaces de couleurs pour l'évaluation d'attributs de couleur d'importance perceptive.

Colorimétrie dans la télévision
par P.J. Darby

Résumé

L'élément principal dans la spécification d'un système de télévision en couleur est l'établissement des coordonnées trichromatiques du tube du récepteur et la détermination du point de référence. On peut alors dériver des équations de transformation afin d'établir les sensibilités spectrales spécifiées des bandes de la caméra.

On peut appliquer les principes colorimétriques aux signaux chiffrés de couleur en appliquant le principe des valeurs primaires de transmission. On considère tout d'abord un système linéaire hypothétique afin d'illustrer les rapports fondamentaux.

Etant donné que le tube du récepteur présente des caractéristiques grille-anode non linéaires, les signaux de sortie du studio devront être corrigés aux rayons gamma. Cependant le système global nécessite une caractéristique grille-anode plutôt plus grande que l'unité afin de compenser les conditions de vision moyennes, et cette non linéarité donne lieu à des modifications en ce qui concerne la chromaticité et la luminance.

On se penche sur le concept de la luminance constante ainsi que sur la reproduction de transmissions pour télévisions en couleur sur des appareils récepteurs en noir et blanc.

Analyse spectrophotométrique automatisée des caméras
par P.A. King et P.J. Marshall

Résumé

On se penche sur une méthode spectrophotométrique pour la mesure des caractéristiques colorimétriques des caméras de télévision en couleur. On décrit en détail un système de mesure et d'analyse avec ordinateur mis au point par IBA. On indique des exemples de résultats obtenus en comparant deux caméras sous forme d'une table de différences de luminance, de saturation, de chroma et de teinte, ainsi que les rapports avec d'autres systèmes d'unités correspondants.

Analyse spectrophotométrique automatisée des contrôleurs
par P.A. King et P.J. Marshall

Résumé

Ce chapitre décrit une méthode spectrophotométrique automatisée pour l'analyse et la comparaison des caractéristiques colorimétriques des appareils de contrôle de télévision en couleur. Les résultats sont exprimés en valeurs trichromatiques ou en coordonnées trichromatiques CIE. On discute de certaines sources d'erreurs qui affectent ces mesures.

Die Lichtmessung
von Prof. R.W.G. Hunt und P.J. Darby

Zusammenfassung

In der Photometrie wird auf der Grundlage der Empfindlichkeit des menschlichen Auges bei verschiedenen Wellenlängen des Lichtes ein System von photometrischen Einheiten erstellt, das direkt auf die in der Physik angewandten radiometrischen Einheiten bezogen ist. Auf dieser Grundlage werden Einheiten zur Messung des Lichtstromes, der Lichtstärke, Beleuchtung, Leuchtdichte, Lichtausbeute, Belichtung und optischen Dichte definiert. Während die Photometrie mit dem Seheffekt des Lichtes im ganzen zu tun hat, beschäftigt sich die Spektrophotometrie mit der Lichtmenge bei jeder Wellenlänge und sie liefert geeignete Meßverfahren für das Studium von Farberscheinungen. Es wird ein Verfahren zum Messen der spektralen Strahlungsverteilung von Lichtquellen beschrieben, dem sich eine Beschreibung

der normalen CIE-Bedingungen für das Messen des spektralen Reflexionsfaktors und der spektralen Durchlässigkeit anschließt. Das Kapitel endet mit einer Erörterung von Lichtquellen, einschließlich dem Plank'schen Strahlungsgesetz, dem Konzept der Farbtemperatur und Definitionen von CIE-Standard-Leuchtkörpern.

Die Kolorimetrie
von Prof. R.W.G. Hunt

Zusammenfassung

Die Kolorimetrie basiert auf dem Umstand, daß der Meßtechniker Farbanpassungen mit zusätzlichen Gemischen von drei Bezugsfarbreizen vornehmen kann, in Mengen, die als Farbwerte bekannt sind. Anhand von Bezugsfarbreizen bei bestimmten Wellenlängen hat die CIE einen Normsatz von Farbwerten in Anpassung an jede verschiedene Wellenlänge des Spektrums definiert und diese Daten bilden den normalen "kolorimetrischen Beobachter 1931". Um negative Farbwerte zu vermeiden, ist aus den Normdaten ein neuer Satz Farbanpaßfunktionen im Sinne der imaginären Primärfarben X, Y und Z bezogen worden. Die Anteile der zu einer Farbanpassung angewandten Primärfarben sind als Farbwertanteile bekannt und können auf einem Farbwertdiagramm bzw. einer Farbkarte aufgetragen werden. Um ein Diagramm zu erzielen, das eine angebracht einheitliche Skala in Bezug auf die wahrgenommenen Farbänderungen gewährt, ist das CIELUV-System 1976 eingeführt worden, das auf den modifizierten Achsen u' und v' aufbaut. In Formeln für Farbunterschiede müssen die Leuchtdichte wie auch die Farbart Berücksichtigung finden und sie benötigen deswegen drei Dimensionen. Für die Auswertung der für die Wahrnehmung wichtigen Farbeigenschaften hat die CIE zwei Farbabstände empfohlen.

Die Kolorimetrie in der Fernsehtechnik
von P.J. Darby

Zusammenfassung

Der erste wichtige Umstand für die Spezifikation eines Farbfernsehsystems ist die Bestimmung der Farbwertanteile der Empfängersichtröhre zusammen mit dem Weißpunkt. Daraus können dann Umwandlungsgleichungen bezogen werden, um die erforderlichen spektralen Empfindlichkeiten der Kamerakanäle festzulegen.

Für die verschlüsselten Farbsignale können kolorimetrische Prinzipien auf dem Konzept der drei Grundsignale angewandt werden. Zur Veranschaulichung der grundsätzlichen Verhältnisse wird zuerst ein hypothetisches lineares System betrachtet.

Da die Sichtröhre ein nichtlineares Übertragungsverhalten hat, müssen die Ausgangssignale aus dem Senderaum gammaentzerrt werden. Das Gesamtsystem erfordert aber ein Übertragungsverhalten, das etwas größer als der Einheitswert ist, um Ausgleich für durchschnittliche Betrachtungsbedingungen zu schaffen und diese Nichtlinearität leitet Änderungen in Farbart und Leuchtdichte ein.

Es werden das Konzept der konstant en Leuchtdichte betrachtet und die Bildwiedergabe von Farbfernsehübertragungen auf Schwarzweißempfängern.

Die computergestützte spektrophotometrische Analyse von Kameras
von P.A. King und P.J. Marshall

Zusammenfassung

Es wird ein spektrophotometrisches Verfahren zum Messen der kolorimetrischen Leistung von Fernsehfarbkameras erörtert und ein von der IBA entwickeltes computergestütztes Meß- und Analysesystem etwas ausführlicher beschrieben. Beispiele der Ergebnisse aus einem Vergleich von zwei Kameras werden in einer Tabelle der Unterschiede in Leuchtdichte, Sättigung, Chroma und Farbton aufgeführt und es werden die Verhältnisse mit anderen relevanten Einheitssystemen genannt.

Die computergestützte spektrophotometrische Analyse von Monitors
von P.A. King und P.J. Marshall

Zusammenfassung

Es wird ein computergestütztes spektrophotometrisches Verfahren für die Analyse und den Vergleich der kolorimetrischen Leistung von Fernsehfarbmonitoren beschrieben. Die Resultate können als Farbwerte oder CIE-Farbwertanteile ausgedrückt werden. Es werden einige der diese Messungen beeinflussenden Fehlerquellen erörtert.

Traducciones

Medida de la luz
por Prof. R.W.G. Hunt y P.J. Darby

Resumen

En fotometría se utiliza la respuesta del ojo humano a luces de diferente longitud de onda para establecer un sistema de unidades fotométricas relacionadas directamente con las unidades empleadas en Física. Basado en esto, se definen las unidades para la medida del flujo luminoso, la intensidad luminosa, iluminancia, luminancia, eficiencia luminosa, exposición de luz y densidad óptica. Mientras que la fotometría se ocupa del efecto visual total de la luz, la espectrofotometría tiene en cuenta la cantidad de luz a cada longitud de onda y proporciona métodos de medida apropiados al estudio de los fenómenos del color. Se describe un procedimiento para la medida de la distribución de energía espectral de fuentes de luz, seguido de una descripción de las condiciones de la CIE normales para la medida del factor de reflectancia espectral y de la transmitancia espectral. El capítulo concluye con una discusión sobre fuentes de luz, incluyendo la ley de radiación de Planck, el concepto de temperatura del color y las definiciones de los iluminantes normales de la CIE.

Colorimetría
por Prof. R.W.G. Hunt
Resumen
La colorimetría está basada en el hecho de que los observadores pueden igualar colores con mezclas aditivas de tres estímulos de referencia, en cantidades conocidas como valores triestímulos. Empleando estímulos de referencia a determinadas longitudes de onda, la CIE ha definido un grupo estándar de valores de triestímulo para igualar las distintas longitudes de onda del espectro, constituyendo estos datos la norma 'observador colorimétrico 1931'. Para evitar valores de triestímulo negativos, se derivó de los datos normales un nuevo grupo de funciones para igualar colores, en términos de primarios imaginarios X, Y y Z. Las proporciones de primarios utilizadas en una igualación de colores se conocen como coordenadas de cromaticidad, las

cuales pueden ser representadas en un diagrama de cromaticidad o mapa de colores. Para obtener un diagrama que ofrezca una escala razonablemente uniforme en relación con los cambios de color percibidos, se ha introducido el sistema CIELUV 1976, empleando ejes modificados conocidos como 'u' y 'v'. Las fórmulas de diferencia de color deben tener en cuenta la luminancia además de la cromaticidad y por ello requieren tres dimensiones. La CIE ha recomendado dos espacios de color para la evaluación de atributos de color importantes desde el punto de vista de la percepción.

Colorimetría en televisión
por P.J. Darby

Resumen

Lo más esencial al caracterizar un sistema de televisión en color es determinar las coordenadas de cromaticidad del tubo de representación del receptor, así como el punto blanco. Entonces pueden derivarse las ecuaciones de transformación para establecer las sensibilidades espectrales de los canales de la cámara.

Los principios colorimétricos pueden aplicarse a señales de color codificadas, empleando el concepto de primarios de transmisión. Se considera primero un sistema lineal hipotético, para ilustrar las relaciones fundamentales.

Puesto que el tubo de presentación tiene una característica de transferencia no lineal, las señales de salida del estudio deben tener corrección gamma. Sin embargo, el sistema total necesita una característica de transferencia algo mayor que la unidad, para compensar las condiciones de visión medias, y esta no linealidad introduce cambios en la cromaticidad y la luminancia.

Se considera el concepto de la luminancia constante y la reproducción de transmisiones de televisión en color en receptores de blanco y negro.

Análisis espectrofotométrico de cámaras operado por computadora
por P.A. King y P.J. Marshall

Resumen

Se discute un método espectrofotométrico para medir el rendimiento colorimétrico de las cámaras de televisión en color. Se describe con cierto detalle un sistema de medida y análisis por ordenador. Se presentan ejemplos de los resultados de comparar dos cámaras en un cuadro de diferencias en luminancia, saturación, cromatismo y tonalidad cromática, dándose las relaciones con otros sistemas de medidas semejantes.

Análisis espectrofotométrico de monitores operado por computadora
por P.A. King y P.J. Marshall

Resumen

Se describe un método espectrofotométrico por ordenador para analizar y comparar el rendimiento colorimétrico de monitores de color de televisión. Los resultados pueden expresarse como triestímulos o coordenadas de cromaticidad CIE. Se discute algunas de las fuentes de errores que afectan estas medidas.

IBA TECHNICAL REVIEW

* Out of Print

The Independent Broadcasting System

The Independent Broadcasting Authority (IBA) is the central body responsible for the provision of Independent Television (ITV, including TV-am, and Channel 4) and Independent Local Radio (ILR) services in the United Kingdom. The IBA selects and appoints the programme companies; supervises the programme planning; controls the advertising; and builds, owns and operates the transmitters. Independent Broadcasting is completely self-supporting, financed by the sale of spot advertising time in the companies' own areas.

More information is contained in *Television & Radio 1985,* the IBA's guide to Independent Broadcasting (£3.90 from bookshops); or in *Independent Broadcasting in 1985,* available free of charge from the Information Office, IBA, 70 Brompton Road, London SE3 1EY.

Printed by The Whitefriars Press Ltd, Tonbridge

IBA

INDEPENDENT
BROADCASTING
AUTHORITY